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SHORT-TERM SEA-LEVEL ANOMALIES AT MONTEREY, CALIFORNIA

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Paul O'Connor

SHORT-TERM SEA-LEVEL ANOMALIES
AT MONTEREY, CALIFORNIA

by

Paul O'Connor

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California

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This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

from the

United States Naval Postgraduate School

ABSTRACT

A method was devised by which short-term deviations from the astronomical tides at Monterey, California were detected and measured in the absence of the predicted tides at Monterey. This was accomplished by comparing the observed tides at Monterey with the predicted tides at San Francisco. The sea-level deviations, or anomalies, that can be found using this method range in duration from several hours to two or three days.

The sea-level variations that were detected during a six-month period at Monterey had magnitudes ranging between +0.9 and -0.8 of a foot and durations ranging from 3.5 to 39.5 hours.

The largest anomalies found are attributed to sea breezes that were unaccompanied by any appreciable atmospheric pressure variations. On the other hand, pressure changes accompanying frontal passages appear to be the dominant cause of other anomalies in spite of wind effects. Time lags in the response of sea level to weather phenomena were as long as three hours.

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1. Purpose.

The ocean tides over the earth are known to be the result of the interaction of the gravitational fields of the sun and moon with that of the earth. These astronomical influences cause periodic undulations in the height of the sea surface which are readily predictable, although their characteristics are complex. It is also well known that there are additional irregular sea-level changes of widely varying duration superimposed upon the regular astronomical tides. It is the purpose of this paper to determine the nature and magnitude of irregular sea-level variations of relatively short duration occurring at Monterey, California, and to determine their causes. A method was devised to detect and measure variations having durations in the range from a few hours to a few days, and these anomalies are dealt with exclusively.

2. Characteristics of the Tide at Monterey.

To make predictions of tidal heights for a given tide station it is necessary to know the harmonic components which make up the total tide; that is, the amplitudes and periods of the lunar and solar tide components as well as their phase differences. These characteristics are obtained by making a Fourier analysis of the tide data obtained at the station. The tide gage at Monterey was installed only recently and no analysis has yet been done.

However, component tides at Monterey can be estimated quite closely from examination of the harmonic tidal constants at standard Coast and Geodetic Survey tide stations located to the north and south of Monterey. Tidal constant data are shown in Table 1 for the station locations illustrated in Figure 1. These components yield a mixed tide at all stations on the coast, with a higher high, lower high, higher low, and lower low tide ordinarily occurring once a day.

From examination of the table, it is evident that the tides at Monterey are similar to those at the adjacent stations. According to the Coast and Geodetic Survey Tide Tables [2], the Monterey tide is referred to San Francisco (Golden Gate) as the reference station for prediction purposes, and bears the following relation to the San Francisco tides (in the form of the corrections to be made to the latter in order to obtain the Monterey tides):

	High Tide	Low Tide
Phase Lag	-1 hr. 16 min.	-58 min.
Amplitude Difference	-0.5 ft.	0.0 ft.

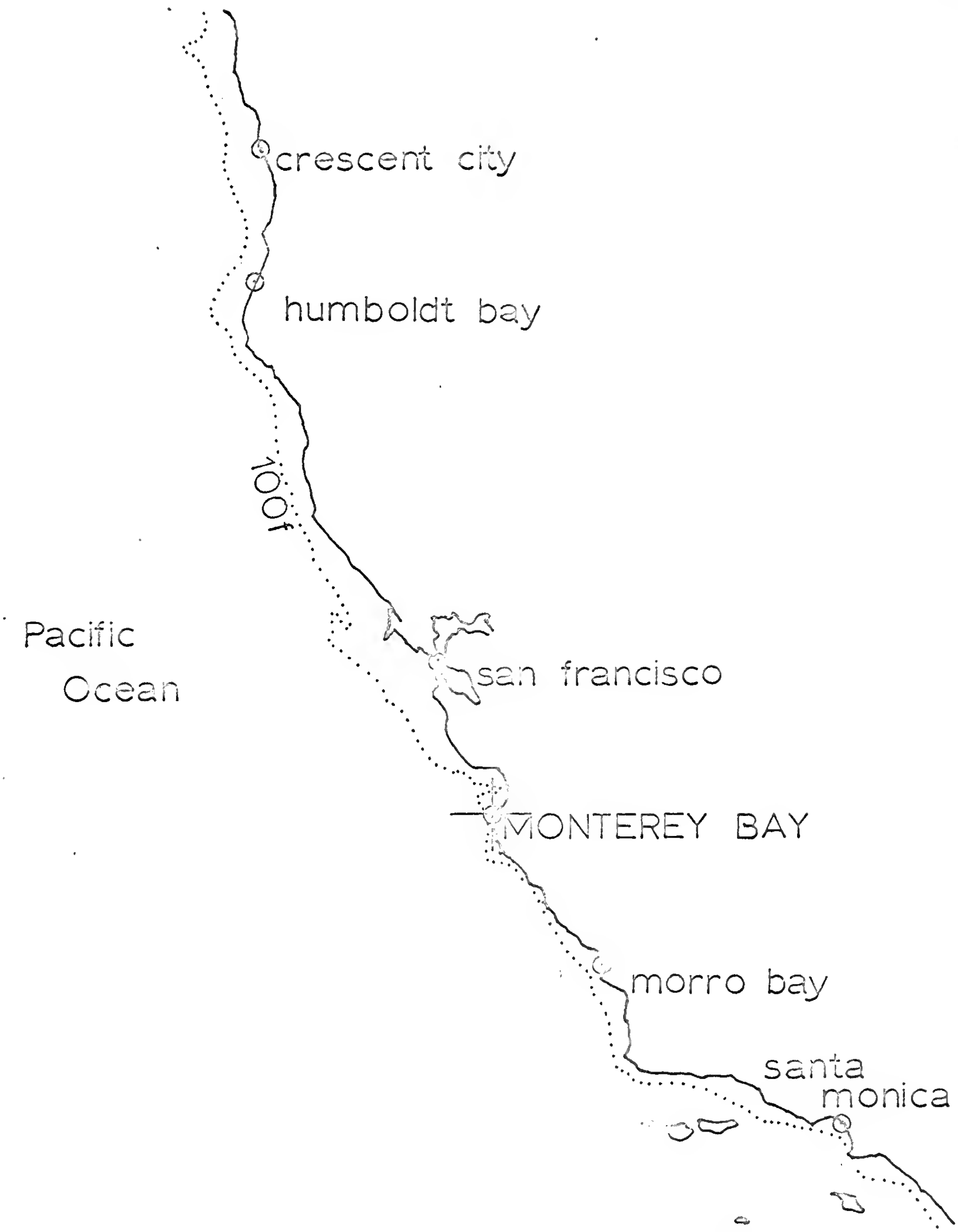

Figure 1. Location of Selected Standard C.&G.S. Tide Stations in California.

Table 1. Tidal Harmonic Constants at Selected Stations
(from the U. S. Coast and Geodetic Survey [1])

	Crescent City	Humboldt Bay	San Francisco	Morro Bay	Santa Monica
			Tide Station		
Diurnal Components:					
Luni-solar (K_1): period 23.93 hr.					
Height (ft.)......	1.28	1.24	1.20	1.00	1.11
Phase (deg.)......	228	240	227	232	208
Principal lunar (O_1): period 25.82 hr.					
Height (ft.)......	0.78	0.77	0.75	0.61	0.71
Phase (deg.)......	212	223	210	220	194
Principal solar (P_1): period 24.07 hr.					
Height (ft.)......	0.39	0.41	0.36	0.27	0.35
Phase (deg.)......	224	237	221	229	204
Semidiurnal Components:					
Principal lunar (M_2): period 12.42 hr.					
Height (ft.)......	2.33	2.06	1.81	1.23	1.64
Phase (deg.)......	211	227	213	190	147
Principal solar (S_2): period 12.00 hr.					
Height (ft.)......	0.58	0.49	0.41	0.32	0.64
Phase (deg.)......	232	247	218	186	141
Larger lunar elliptic (N_2): period 12.66 hr.					
Height (ft.)......	0.50	0.42	0.40	0.26	0.39
Phase (deg.)......	186	201	206	166	125
Luni-solar (K_2): period 11.97 hr.					
Height (ft.)......	0.14	0.13	0.13	0.10	0.19
Phase (deg.)......	217	239	206	172	133

The above data are based on the following observations:

	Series	Duration
Crescent City:	1939	1 year
Humboldt Bay:	1911-12	1 year
San Francisco:	1935	1 year
Morro Bay:	1919	163 days
Santa Monica:	1938	1 year

Due to the close relationship between the Monterey and San Francisco tides and the availability of the hourly predicted tides at San Francisco, the latter station was used as a reference to which Monterey tides were compared in order to obtain the local sea-level anomalies.

The Monterey tide data were obtained from a standard recording tide gage installed on Monterey Municipal Wharf No. 2, as shown in Figure 2. It is operated by the U. S. Naval Postgraduate School under an Office of Naval Research Foundation Grant. Recording began on 3 July 1963 and was continuous throughout the period of investigation with only a few minor exceptions. For the purposes of this study, the data have been analysed on an hourly basis from 1 August 1963 through 31 January 1964.

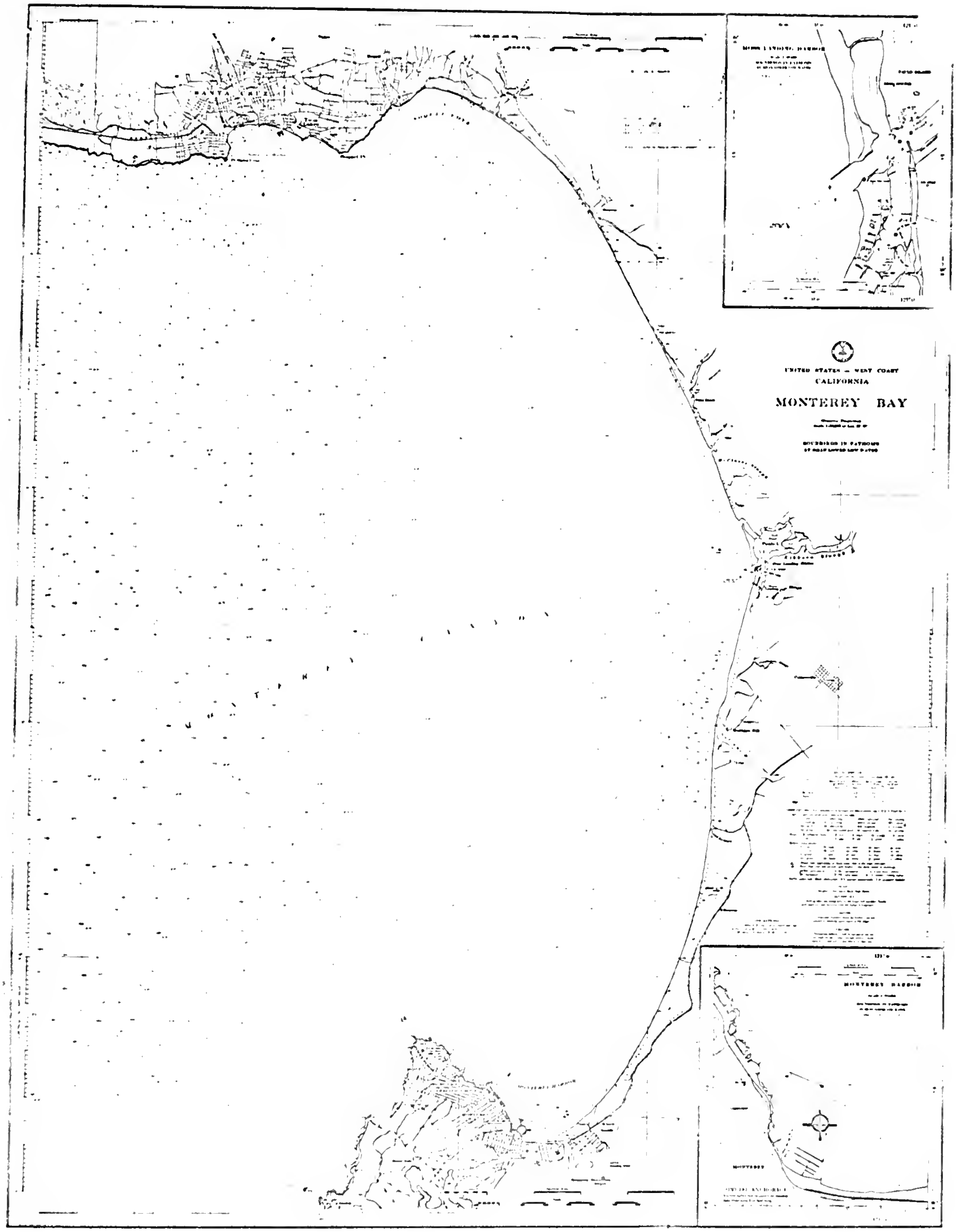

Figure 2. Monterey Bay, California (from C.&G.S. chart 5403). Tide gage location shown by -⊕-.

3. Preliminary Analysis of Tide Data.

As mentioned above, non-astronomical variations in sea level, both high and low, occur at irregular time intervals along any ocean boundary In this paper, any such deviation from the astronomical tide will be referred to as a sea-level anomaly. This investigation will be concerned exclusively with short-period anomalies, such as might be observed during a storm, which last from a few hours to two or three days.

When predicted tides are available for any given station, sea-level anomalies of any duration can be obtained readily by subtracting these tides from the tides actually observed, using preferably an hourly comparison. Since there are no predicted hourly tides available for Monterey, it was necessary to devise a method by which local anomalies could be identified and measured without reference to astronomic values

In the first attempt to do this, the hourly tide data from Monterey were plotted independently against time. It was hoped that periods of irregular water level could be detected visually. The most notable result was the smoothness of the curves which showed no obviously anomalous values. Therefore, this method was abandoned.

The next approach followed involved comparison between the Monterey and San Francisco tides. It entailed plotting separately the envelopes of the two high waters (higher high water and lower high water) and the two low waters (lower low water and higher low water) at Monterey with time, each normally occurring once a day. The same was done for San Francisco using the predicted tides, and the two sets of data were compared. It was hoped that this approach would allow detection and measurement of anomalies that may have occurred at times of high and low

water. The thought behind this approach was that any deviation in the periodic trend of the high and low tides at Monterey would represent an anomaly and it would be directly measurable. A serious drawback of this approach is that it yields no information on anomalies during the approximately six-hourly intervals between each successive high and low tide. The curves for both stations proved to be very similar in shape, with deviations occurring in the Monterey envelope as expected. However, the six-hourly sampling was not sufficiently detailed to yield significant data and this approach was abandoned.

Another attempt at solving the problem involved a direct comparison on an hourly basis of the observed Monterey tides with the predicted San Francisco tides (provided by the Coast and Geodetic Survey). The hourly values for the two stations were off-set by one hour to account for the average time difference between them, and then the difference between the observed and predicted values was calculated. The assumption behind this attempt was that because the astronomical tides have nearly the same components at the two stations, the resulting water-level differences, when plotted against time, should be an almost flat curve with only small regular changes, on which anomalies would be superimposed. However, the plot of the differences against time revealed a nearly smooth curve, similar to an astronomical tide curve, with a maximum range of up to 3.1 feet and a period of about 25 hours. Irregularities were observed in the plot and were assumed to be anomalies; however, their amplitudes were small in comparison with that of the periodic component evident in the plot, and it proved impossible to measure their magnitude or duration with any degree of accuracy.

These attempts showed the sea-level anomalies at Monterey to be smaller than was first expected; accordingly, the task of finding a means of identifying and measuring them proved to be more formidable than anticipated.

4. Analysis Method Developed.

a. Construction of Observed and Astronomical Tide Charts

The method finally arrived at involved the construction of a tide chart of specific design. The construction is based upon the fact that tides at Monterey very nearly repeat themselves in the lunar period of about 25 hours. Thus, for any point on the tidal cycle the elevation 25 hours later is approximately the same. Since the 25-hourly astronomically induced variation in the tidal cycle is very small and regular, it was decided to compare water levels on a 25-hour basis in search of anomalies.

Accordingly, for a given month at Monterey, a chart of hourly heights was constructed in the manner shown in the example in Figure 6 for November 1963. The hourly heights were plotted on a grid in such a manner that there is a 25-hour interval horizontally between each column of values. Hence, when read horizontally the chart yields a 25-hourly comparison. Vertically, each column on the tidal chart shows the hourly sea levels for a 25-hour period.

The upper left-hand value is the water level at 0000 on the first day of the month. Column one ends with the water level at 0000 on the second day of the month. The second column starts with 0100 on the second day and ends with 0100 on the third, and so on. Since each column contains water levels for two days, the top of the column is labeled with the days represented in it.

Contours of equal tide height were then drawn on the resulting grid at one-foot intervals. The result was an undulating topography of

high and low tides. The basis of this method was the assumption that purely astronomical tides would produce a smoothly rolling topography; whereas, the topography associated with the actual sea level would display irregularities of non-tidal origin which would lend themselves to measurement. This proved to be the case.

A chart of this design was produced for each month from August 1963 through January 1964 using the observed hourly data at Monterey. These charts, shown in Figures 3 through 8, give a graphical presentation of the actual tidal variations over one month. Using the same procedure, astronomical tide charts were constructed for San Francisco for the same months using the predicted hourly heights for San Francisco. These charts are shown in Figures 9 through 14. The height values shown on the two sets of charts are not comparable due to the fact that the San Francisco tides are referred to Mean Lower Low Water and the Monterey tides are referred to an arbitrary datum plane.

b. Characteristics of the Tide Charts

Examination of the charts for San Francisco and Monterey revealed the following general characteristics:

(1) San Francisco: astronomical tides (Figures 9 through 14)

The general pattern is one of elongate centers of high and low values, representing high and low tides. The major tides (HHW and LLW) are indicated by the centers having extreme values, whereas the minor tides (LHW and HLW) form ridges and troughs in the pattern. Cols also occur, and represent those intervals of the month when interchange occurs between the major and the minor tides; for example, the times of

the month when the envelopes of HHW and LHW intersect.

The contours are relatively smooth with no major irregularities. Where the field of values is flat, representing intervals of small water-level variations, small irregularities in the contours occur. These can be attributed to the fact that the heights are characteristically recorded only to the nearest tenth of a foot. Additionally, there are small errors of secondary magnitude in the interpolations between the plotted values which constitute a low-level "background noise".

(2) Monterey: observed tides (Figures 3 through 8)

In comparison to the San Francisco charts, these are irregular in detail but display the same mean pattern. The charts for some months show considerably more irregularity than others.

c. Construction of Astronomical Tide Charts for Monterey

The smooth patterns that are exhibited by the San Francisco charts are to be expected since they are the result of astronomical influence alone. If similar charts could be prepared for Monterey they would be expected to display similar uniformity. Therefore, the irregularities in the Monterey charts prepared from the observed hourly heights can be attributed to non-astronomical causes.

Even though the irregularities in the Monterey observed tide charts became obvious in this type of presentation, the task remained to measure the magnitude and duration of the sea-level deviations. Ideally this would be done by superimposing charts of the observed and predicted tides at Monterey and taking the difference between them. However, without the astronomical tides for Monterey, charts of predicted tides could

not be prepared directly, but they were closely approximated in the following manner.

It was observed that when a predicted tide chart for San Francisco for a given month was placed under the observed tide chart for Monterey, and examined on a light table, the contours of sea-level elevation coincided over most of the chart remarkably closely in form when the two charts were properly aligned. The coincidence in the patterns was most marked in months of quiet weather (e.g., August as shown in Figures 3 and 9). Even in months showing numerous irregularities (e.g. January, Figures 8 and 14), the irregularities were largely localized on the chart so that the overall pattern was evident. This mean pattern was found to coincide with the San Francisco contour pattern and was, therefore, assumed to represent the astronomical tide at Monterey.

Charts closely approximating the astronomical tides at Monterey were then constructed for each month by underlaying the San Francisco chart and using the contours on it as a guide in smoothing the irregularities in the Monterey tides. The properties of the contours that served this purpose included their orientation, curvature, and gradient, but not their heights.

In the overlay process, the Monterey chart was off-set in time by one hour and 15 minutes from San Francisco in order to account for the difference in the time of the high tides between the stations (note table on p. 2), and smooth contours in the high tide portions were drawn on the Monterey chart. The off-set was then changed to one hour, the time difference of the low tides between the stations, and smooth low-water contours were completed. The resulting astronomical tide charts

for Monterey are shown in Figures 15 through 20.

d. Construction of Anomaly Charts and Determination of Anomalies

The observed and the astronomical tide charts for Monterey for each month were next compared by superimposing them on a light table. Those areas of the charts where equivalent contours deviate from one another were assumed to represent anomalies, and are plotted in Figures 15 through 20.

In the charts an anomaly is displayed by the divergent portions of individual contours, the area between a given pair being shaded for identification. The cross-hatched areas are anomalies of 0.2 of a foot or less and were ignored. The width of the shaded areas between contours is not directly a measure of the magnitude of an anomaly but depends also on the water-level gradient. Thus, anomalies occurring in those parts of the charts where gradients are weak appear as large deviations, but where the gradients are large, the contour separation associated with anomalies of equivalent magnitude is much smaller. A given anomaly lasting so many hours would show up as a series of such contour pairs aligned vertically on the chart and extending over a period of so many hours. An example is shown in Figure 19 for 6 and 7 December when an anomaly occurred lasting 16.5 hours.

The magnitudes of the anomalies occurring during the six-month period were measured directly from the superimposed Monterey charts by taking the difference at each grid point between the observed and the astronomical tides. The anomalies thus found are graphed in Figures 21 through 26.

Separating anomalous water levels from the tide data did not prove to be a clear-cut procedure in all cases. Therefore, the following two criteria were set up to aid in identification of anomalies:

(1) A large deviation in the field of water-level values which appeared at only one point and was not reflected at adjacent grid points, that is, a singularity, was assumed to be a data error. These singularities, which numbered not more than two in a given month, were ignored.

(2) Due to the fact that the water levels were recorded to the closest 0.1 of a foot on both charts, differences between the charts amounting to 0.2 of a foot or less were ignored. An exception to this rule is made where these smaller values appeared in a sequence of larger hourly water-level values. In this case the small values were considered to be part of a larger anomaly.

5. Observed Anomalies.

Application of the procedure described above to the Monterey tide data for the months of August 1963 through January 1964 resulted in the identification of 54 periods of anomalous water levels of sufficient magnitude and duration to be measured (i.e., greater than 0.2 of a foot). In order to eliminate from consideration a large number of small anomalies, the additional limitation was arbitrarily established that only those anomalies amounting to 0.3 of a foot or greater for at least three hours would be included in the analysis. This reduced to 19 the number of periods which were investigated in detail. These are tabulated in Table 2 and graphically portrayed in Figures 21 through 26.

The first two columns in Table 2 list the date and time of the appearance of each anomaly. The time was taken as the closest hour at which the water-level deviation exceeded 0.2 foot. The duration listed is the number of hours the anomaly lasted from the time of on-set until the water-level deviation ultimately diminished to less than 0.2 foot. The magnitude is the largest value of the anomaly, whether positive or negative, found during the period. If more than one main peak occurred, the extreme values of each are listed.

The anomalies varied in magnitude between the extremes of +0.9 and -0.8 of a foot and ranged from 3.5 to 39.5 hours in duration. They displayed no uniform pattern, six being positive only, eight being negative only, and five involving both positive and negative water levels during the period. In the last group, negative values preceded positive values in four cases. Some anomalies were in the form of a simple rise or fall of the water level. Others displayed apparent oscillations with periods

Table 2. Compilation of Observed Anomalies

DATE	TIME	DURATION (hr.)	MAGNITUDE (ft.)	DOMINANT WEATHER	SEA LEVEL PRESSURE (mb.)	SURFACE WIND SPEED(kt.) & DIRECTION	GRAPH NO.
24 Aug.	9am	11	-0.7 0.9	High pressure ridge	Inc 18.1 then dec 15.7. (Mostly steady, max 18.2)	Calm to NW 7. SE last 2 hr. (Mostly calm, max SW 4)	21(a)
25 Aug.	10am	11	-0.8 0.9	High pressure ridge	Inc 16.5 then dec 13.3. (Steady 16.0)	NW max 8. SW max 6 last 2 hr. (Calm)	21(b)
30 Oct.	10:30pm	3.5	-0.5	High pressure ridge	Steady at 20.2 with 0.5 dec at 1 am (Steady 20.2)	Calm to SE 3 (Direct. variable max 4)	21(c)
3 Nov.	2:30pm	4	-0.3	High pressure ridge. Weak cold front in So. California	Max 20.2, min 19.8. (Slight inc 16.2 then dec 14.8)	SW 6-10 to SE 2-4 (Max NW 5)	21(d)
5 Nov.	4pm	9.5	0.4	Apparent cold front passage at 6:20 pm	Dec 05.4, then inc 11.0 in 3 steps	Southerly max 20, gust to 37	22(a)
14 Nov.	3:30pm	6.5	0.5	Cold Front passage 7:20 pm	Inc 16.2 in 2 steps (Max 14.1 at 11 am, then decreasing)	SW 7 marked decrease after frontal passage	23(a)

1. "inc 18.1" means "increased to 1018.1 mb." (or kt. for wind); "dec" means "decreased to".

2. Information in parentheses is for 6 hours prior to the onset of the anomaly.

Table 2 (continued)

DATE	TIME	DURATION (hr.)	MAGNITUDE (ft.)	DOMINANT WEATHER	SEA LEVEL PRESSURE (mb.)	SURFACE WIND SPEED(kt.) & DIRECTION	GRAPH NO.
19 Nov.	11am	39.5	0.8	Low pressure area with frontal passage afternoon of 19th	Dec 05.2 at 2100, then irregular inc 12.6 (Decreasing from 10.7)	Southerly and westerly Mar 12 until 6 am 20th. Then inc NW 16, gust 24 by 5 pm. (Increasing throughout)	22(b)
22 Nov.	2am	4.5	-0.5	High pressure ridge	Steady at 23.0, then inc 26.3 (Increasing throughout)	Mostly SE. Max 4. (Decreasing throughout)	23(b)
6 Dec.	4:30pm	16.5	0.6 -0.7 0.5	High cell to NW. Possible cold front passage, but no associated weather	Inc 24.1 from 21.7 (Inc 24.1, then decreasing)	Mostly SE 8-12 (Less than 5)	23(c)
7 Dec	10pm	23	0.8	Cold front passage pm on 8th	Dec 10.1 from 20.8 in 2 steps (Slow dec throughout)	Variable from calm to SW 9. Gust 15. (Slow decrease max 6)	24(a)
2 Jan	2am	4	-0.5	Very weak cold front passage	Steady first 3 hr., then increasing. (Steady increase)	SE less than 5 (Variable max 4)	24(b)
3 Jan	3am	4.5	-0.6	High pressure ridge	Steady first 4 hr., then increasing. (Increasing)	SE 5-10 (SE 6-10)	24(c)
4 Jan	4am	4	-0.5	High pressure area	Steady first 3 hr., then increasing. (Inc 27.7, then decrease)	Variable max SE 6. Calm to SE 6.)	24(d)

Table 2 (continued)

DATE	TIME	DURATION (hr.)	MAGNITUDE (ft.)	DOMINANT WEATHER	SEA LEVEL PRESSURE (mb.)	SURFACE WIND SPEED(kt.) & DIRECTION	GRAPH NO.
16 Jan.	1:30am	6.5	-0.4	High pressure ridge. Cold front 300 NM NW	25.0 ± 1 mb. (Slow increase throughout)	SE max 4. (Less than 5)	25(a)
20 Jan.	5pm	8	0.7	Cold front passage 10pm. Low pressure area.	Dec 00.3, 2 mb. increase, dec 00.1, inc 06.3 (Steady decrease)	Southerly max 28. Gust 52. (Southerly inc 28, gust 40)	25(b)
21 Jan.	5pm	8	0.6	Low pressure trough	Dec 04.8 by 8 pm, then increase 07.2 (Dec throughout)	SW max 14. Gust 23. (Southerly max 12, gust 24)	25(c)
23 Jan.	2am	8	-0.5	High pressure ridge	Steady inc 24.7 (Steady inc 18.8)	Southerly max 4 (Southerly max 8)	25(d)
23 Jan.	12pm	10.5	-0.4 0.7	High pressure ridge	Inc 28.8 in 2 steps. (Steady inc 25.2)	Calm (Mostly calm, some SE max 4)	26(a)
25 Jan.	1:30am	17.5	-0.5 0.4	High pressure ridge	Dec 17.7 in 2 steps. (Dec 27.1)	Mostly SE, max 7. (Mostly calm. Max ESE 4.)	26(b)

ranging from four to 14 hours.

Three anomalies were recorded for the months of August through October, and 16 for the months of November through January. It is probable that the number of anomalous sea-level occurrences was fewer than normal because unusually mild weather prevailed at Monterey throughout the period.

6. Weather Conditions Associated with Anomalies.

The weather conditions that prevailed at the time of each anomaly are summarized both in Table 2 and in Figures 21 through 26. The weather information presented in Table 2 is as follows:

(1) Dominant Weather: the synoptic weather conditions that prevailed during the anomaly period, such as high pressure cell, frontal passage, etc.

(2) Sea-Level Pressure: the local atmospheric pressure tendency and pressure extremes during the anomaly period. Pressure data were recorded at the U. S. Naval Air Facility, Monterey.

(3) Surface Winds: the local wind-speed variations and extreme winds, with directions. These data were also recorded at the Naval Air Facility. Due to the sheltered location of the station, the tabulated wind speeds are not as high as would have been recorded over the ocean. Therefore, the wind speeds should be considered only relatively; that is, an increase in the wind speed at the Air Facility would correspond to an increase over the ocean. At wind speeds of less than five knots, the direction is probably not indicative of the winds over the bay and adjacent ocean area; however, at higher speeds the direction seems to be representative.

The hourly pressure and wind data obtained from the Naval Air Facility were the best data available. It would have been desirable to use wind data which were recorded in Monterey Bay or at least along the shore line, but none were available.

7. Causes of Anomalies.

The anomalies measured have durations and magnitudes such as changing weather conditions would be expected to produce. However, an inspection of Table 2 and the associated graphs of the anomalies reveals the fact that there are no clear-cut general relationships between the meteorological phenomena and the anomalous sea levels. In some cases expected relationships appear, but not in others.

Because water-level variations may result from changes of both wind and pressure acting on the ocean surface, these causes will be considered separately and then together.

a. Atmospheric Pressure

Comparison of the pressure and anomaly curves in Figures 21 through 26 reveals seven cases in which an inverse relationship between the two quantities is clearly evident--24 and 25 August, 19 November, and 16, 20, 21, and 23 January. There are two cases, on 7 December and 25 January, when this relationship occurred during part of the period only. In the remaining 10 cases there was no relationship evident. The latter included one case in which large water-level variations occurred but no pressure change was recorded (6 December), and one in which the opposite situation was the case (5 November). In general, considering all 19 cases, when pressure variations were large, then water-level changes were large, and vice versa. Thus, anomalies appear to be related to atmospheric pressure changes, but the nature of the relationship is not clear.

The influence of atmospheric pressure may be considered from two

standpoints; the regional pressure field in the northeast Pacific and over the Central California coast, and the local pressure field at Monterey.

Examination of the weather maps for the six-month period under investigation indicates that large-scale regional pressure changes generally occurred at much slower rates than are needed to explain the rates of sea-level change exhibited by the observed anomalies. Therefore, regional pressure changes are not considered as contributing to the observed sea-level changes. With regard to the possible effects of local pressure changes, water-level anomalies of 0.5 foot that commonly occurred, often in three hours or less, would require a change in the static atmospheric pressure of 15 mb.; however, the maximum rate of pressure change observed at Monterey was only 8 mb. in nine hours (on 7 December). Accordingly, local pressure changes are not sufficient to fully explain most of the anomalies.

Commonly, both pressure and wind effects are present simultaneously, as in the passage of a storm system. In order to consider only the effects of pressure, five cases were examined in which anomalies occurred with low wind speeds so that wind-induced changes were minimized. The examples considered occurred on 30 October, 21 November, 16 January, 23 January, and 24 January. Each of these periods has the following conditions in common: (a) no recorded wind speed in excess of four knots, (b) atmospheric pressure of 1020 mb. or higher, (c) negative anomalies for all or part of the period (the anomalies were negative in all cases except on 23 January), and (d) high pressure and low wind speeds for six hours prior to the onset of the anomaly.

The pressure changes on 30 October and 16 January were quite small during the periods of the anomalies and these cases will not be considered. On 21 November, the atmospheric pressure versus sea-level relationship, shown in Figure 23(b), appeared to alternate at different times during the anomaly. In two instances when the pressure was increasing, at 3 a.m. and 7 a.m., sea-level was falling, which is the effect that would be expected from isostatic considerations, but at 6 a.m., with increasing pressure, the water level was rising. Thus a one hour lag appears to have occurred between the pressure change and the water-level reaction.

Figure 25(d) for 23 January shows a marked pressure increase throughout the entire anomaly period, whereas a negative sea-level deviation is evident during most of the same period. However, the anomaly disappeared while the pressure continued to rise. Similar conditions are found in Figure 26(a) for the morning of 24 January except that the pressure increase was not as great, and the anomaly changed from a negative to a positive value before finally disappearing.

Hence, it can be seen that the pressure variations alone do not satisfactorily explain all of the sea-level deviations.

b. Surface Wind

The wind can cause anomalous water levels in two ways. First, water may be piled up along the coast or blown offshore as a result of the tangential stress exerted by the wind on the sea surface whenever there is a component normal to the coast. Second, wind-generated waves transport water in the direction of wave propagation. The two effects

are difficult to separate and no attempt was made to do so.

The tide gage is situated in a location (Figure 2) that is sheltered from seas from all directions except those produced by north winds, which are uncommon. Waves from all other directions suffer intense refraction, so that the mass transport of water into the southern end of Monterey Bay by wind waves is considered negligible. Accordingly, the effect of waves in producing anomalies will be ignored.

Studies of the effects of the wind stress in piling up water against a coast, carried out on broad, shallow continental shelves, show that the piling up is greatest at the shore line and extends offshore no more than 10 to 20 miles. Off the Pacific Coast where the continental shelf slopes comparatively steeply, the amounts of piling up and the distance this effect extends offshore can be considered to be much less.

There are two types of local winds that could have a significant effect on the water level: the sea breeze, which is common in the afternoon at Monterey, and storm-generated winds. The sea-breeze effect is best illustrated by the graphs in Figure 21(a) and (b) for 24 and 25 August. During the first six hours in each case the pressure was relatively high and the onshore wind became established. (It is not possible to separate the wind and pressure effects in this example.) With reference to the tide-gage location, onshore winds are considered as those blowing from the north ±45 degrees, whereas offshore winds are those blowing from the south ±45 degrees. Throughout the initial six hours in both cases the water level was lower than that predicted by the astronomical charts, but as the sea breeze (onshore wind) continued and strengthened, the sea level rose and the anomaly became positive. This condition

was maintained until the winds diminished or changed direction, at which time the anomaly decreased and finally disappeared. Because of missing data, it is possible that the water-level oscillations on these two days were continuous and extended beyond 9 p.m. on the 25th. If they were continuous, the period of oscillation would have been about 12 hours.

These two examples may be contrasted with those occurring in the early morning on 2, 3, and 4 January, as shown in Figures 24(b), (c), and (d), when there was no persistent sea breeze established during the prior afternoon. Rather, there was a short period of weak onshore winds, occurring approximately at mid-day, followed by weak offshore winds which persisted until the anomaly appeared. Thus, it seems that sea level was lowered by the continuation of offshore breezes. Neither wind nor pressure alone appear to be of sufficient strength to cause the observed sea-level depression of 0.5 to 0.6 of a foot. Additionally, the rise to zero anomaly is not explained by either effect.

Well-defined storm systems with attendant frontal passages at Monterey occurred on 14 and 19 November, 7 December, and 20 January. Each of these storms resulted in positive sea-level anomalies regardless of the wind strength or direction.

Figure 23(a) illustrates the storm of 14 November. The sea level rose from zero to 0.4 of a foot during a period of steady pressure and offshore winds. This increase in sea level is evidently not explained by the weather conditions since an offshore wind would be expected to cause lowered water levels. However, one hour after the marked pressure increase began, the anomaly started to decrease. Hence, the interaction of the wind and pressure with sea level is not clearly

explained in this example.

The storm period which started on 19 November, graphed in Figure 22(b), showed a generally rising sea level with decreasing pressure, the maximum sea-level deviation of 0.8 of a foot occurring three hours after the pressure minimum. During the first 15 hours of the anomaly, the wind was predominantly offshore at speeds of up to 12 knots with a peak gust of 22 knots. When the pressure increased, the sea-level height decreased, but a positive anomaly was maintained for an additional 26 hours. This may have been due to the fact that the wind shifted to northwesterly (onshore) and increased slightly in speed. Thus, it appears in this case that the water level was primarily influenced by atmospheric pressure with the wind exerting a secondary influence.

The changing sea level on 7 December, shown in Figure 24(a), is unusual in that water-level variations up to 0.8 of a foot occurred with little or no pressure change, followed by an eight-millibar pressure drop during which the water level remained steady. The anomaly did originate during a period of decreasing pressure, but thereafter there seems to be no correlation between the sea level and the pressure. The wind probably was not an important factor since it was comparatively weak during the entire period. There is an increasing trend in the anomaly at the end of the graph, but the data beyond this point were missing.

One final example of a storm-induced anomaly will be considered. The winds associated with storms in this area are generally from the south, and therefore offshore locally in Monterey Harbor; accordingly, they presumably would tend to lower the sea level at the tide gage. At the same time, the low pressure which accompanies a storm would tend to raise the

sea level. These two forces, having opposite effects on the sea surface, tend to cancel each other and result in smaller anomalies. This effect is demonstrated in Figure 25(b) for 20 January. On that date there was a rapid pressure drop with an equally rapid increase in the height of the sea level. The wind that prevailed during the anomaly period was from the south (offshore) and quite strong. The maximum hourly value was 28 knots with a peak gust of 52 knots. These strong winds appear to have caused a depression in the maximum value of the anomaly. Again in this case, there is a one-hour lag between the decrease in magnitude of the anomaly and the pressure increase. In this instance, both processes are quite rapid, and the inverse relation between the pressure and sea level is clearly illustrated.

8. Conclusions.

A method has been developed by which short-term sea-level anomalies in the range from a few hours to several days may be detected and measured at a given tide station without the need for the predicted astronomical tides at that location. The method should be usable wherever the astronomical tide variations can be approximated by using data from an established standard tide station nearby.

Using hand drawn methods, the accuracy of the constructed tide charts is limited to approximately 0.2 of a foot. However, a significant increase in the accuracy of the charts would result by reducing the time interval between the observed sea-level heights and by using a computer to contour the tide charts and pick out anomalies. This would require a computer capable of printing larger graphs than the model that is available at the U. S. Naval Postgraduate School.

The sea-level variations that were detected at Monterey had magnitudes ranging between +0.9 and -0.8 of a foot and durations ranging from 3.5 to 39.5 hours. Numerous anomalies less than three hours long were seen on the anomaly charts; however, none of these were greater than 0.2 of a foot in magnitude. The longest anomaly period observed was associated with the passage of a storm through the Monterey area. It appears that the sea-level variation must exhibit a relatively high rate of change in order to be detectable by this system. Therefore, it is probable that the duration of the longest deviation in sea level that this system can detect would be determined by the duration of the storm causing that deviation.

It was found that a persistent sea breeze, unaccompanied by any

significant atmospheric pressure change, will pile up water along the coast, resulting in a positive water-level anomaly. Sea breezes lasting nine to ten hours were responsible for the largest anomalies found during the entire six-month period. On the other hand, significant pressure changes accompanying frontal passages appeared to be the dominant force in the formation of some sea-level anomalies and masked all but the strongest wind effects.

It was noted that in several instances the water level reacted quickly to atmospheric pressure changes. One-hour lags were readily observed in two cases, but during some anomalous periods the lag may have been as long as three hours. Hence, variations in the sea-level height which are caused by slowly changing processes will not produce anomalies that would be evident in this type of presentation.

9. Acknowledgements.

The writer would like to express his sincere appreciation to Professor Warren C. Thompson of the Department of Meteorology and Oceanography, U. S. Naval Postgraduate School, for his invaluable assistance throughout the preparation of this paper. Had it not been for his recommendations, suggestions, and helpful criticism I would not have been able to complete this project in the time available.

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Finally, I would like to say thank you to my wife for her typing assistance; but primarily for the encouragement and understanding she provided during the course of this investigation.

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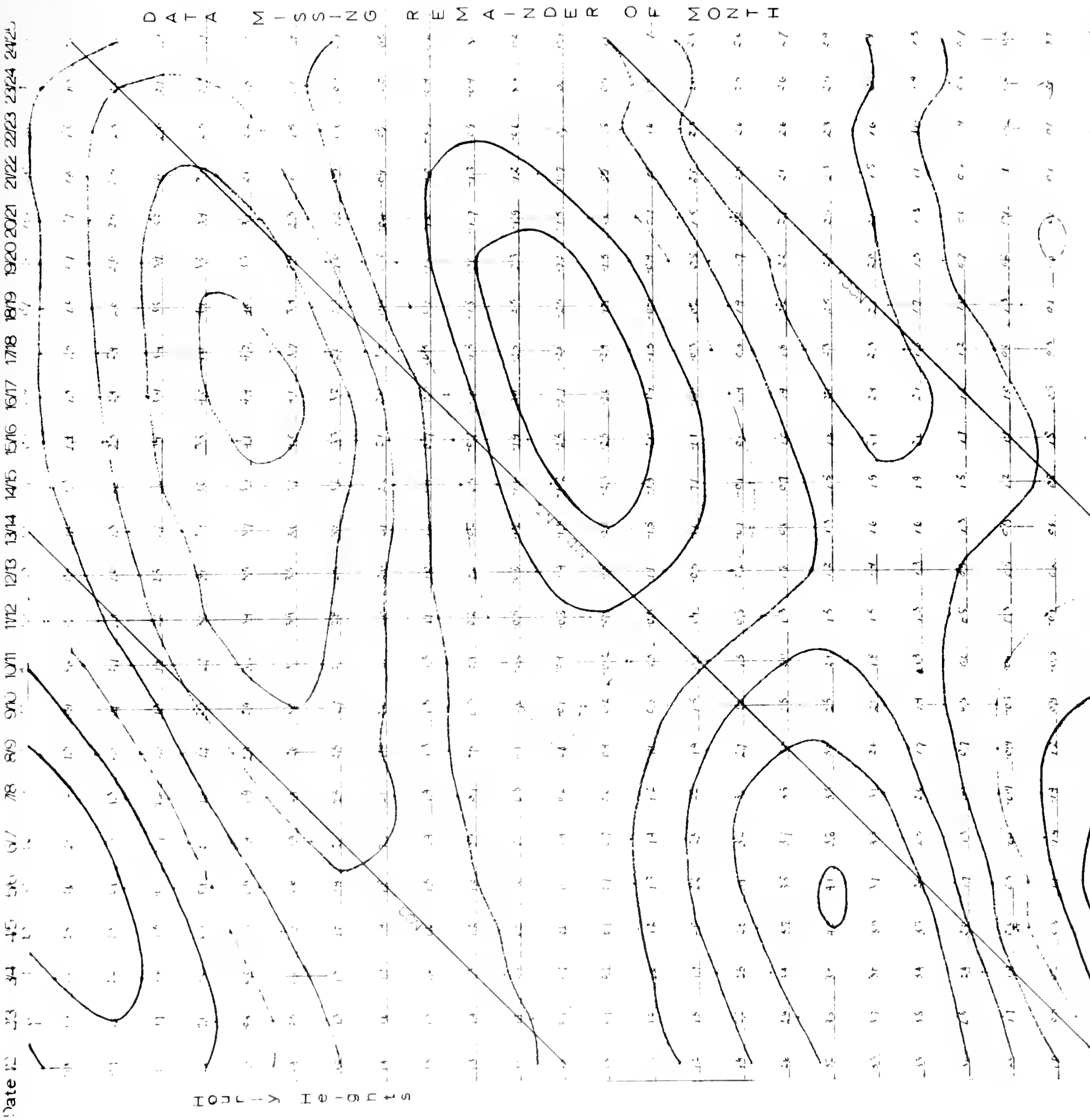


Figure 3 Observed Tides at Monterey in August, 1963.

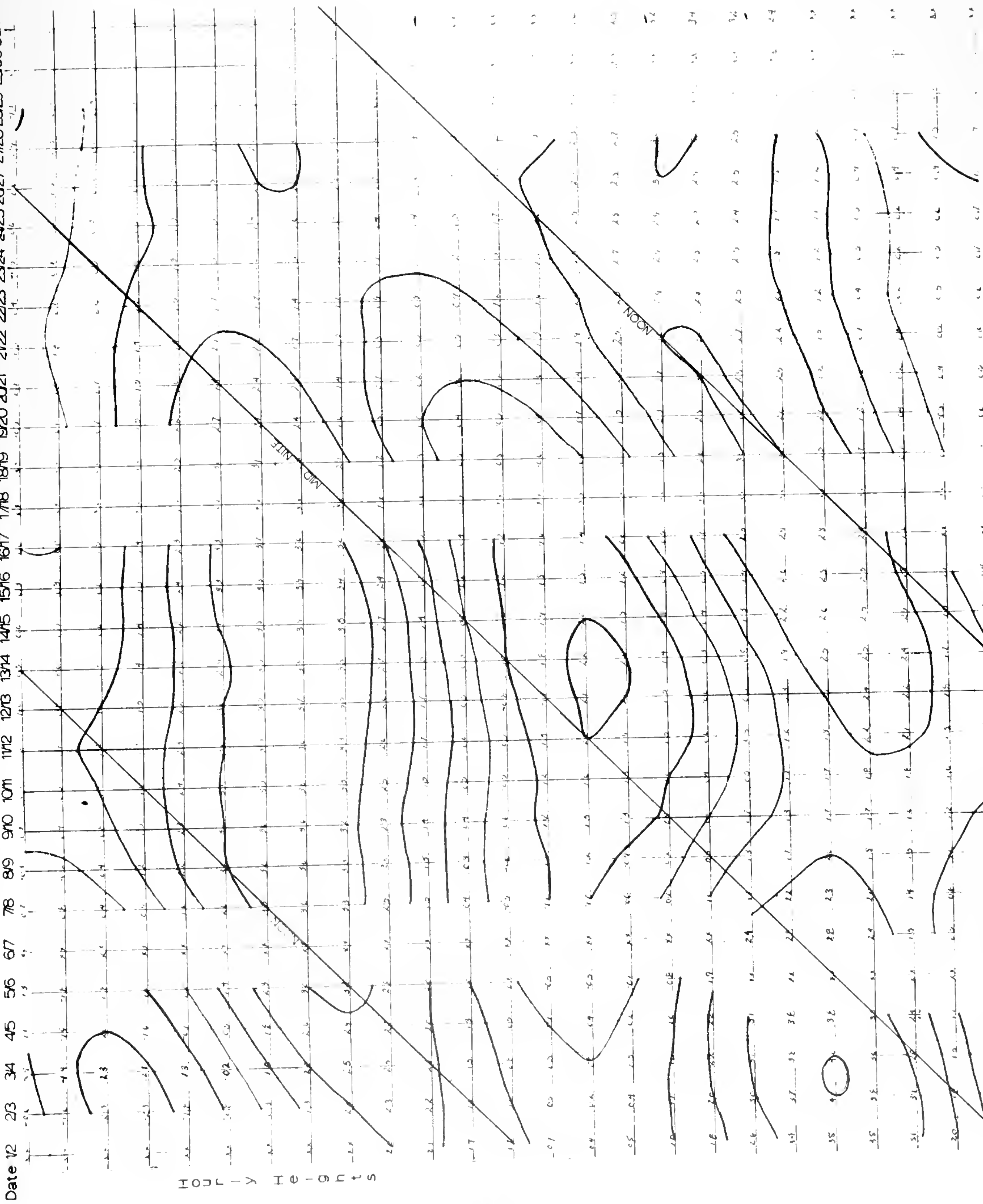


Figure 4. Observed Tides at Monterey in September, 1963

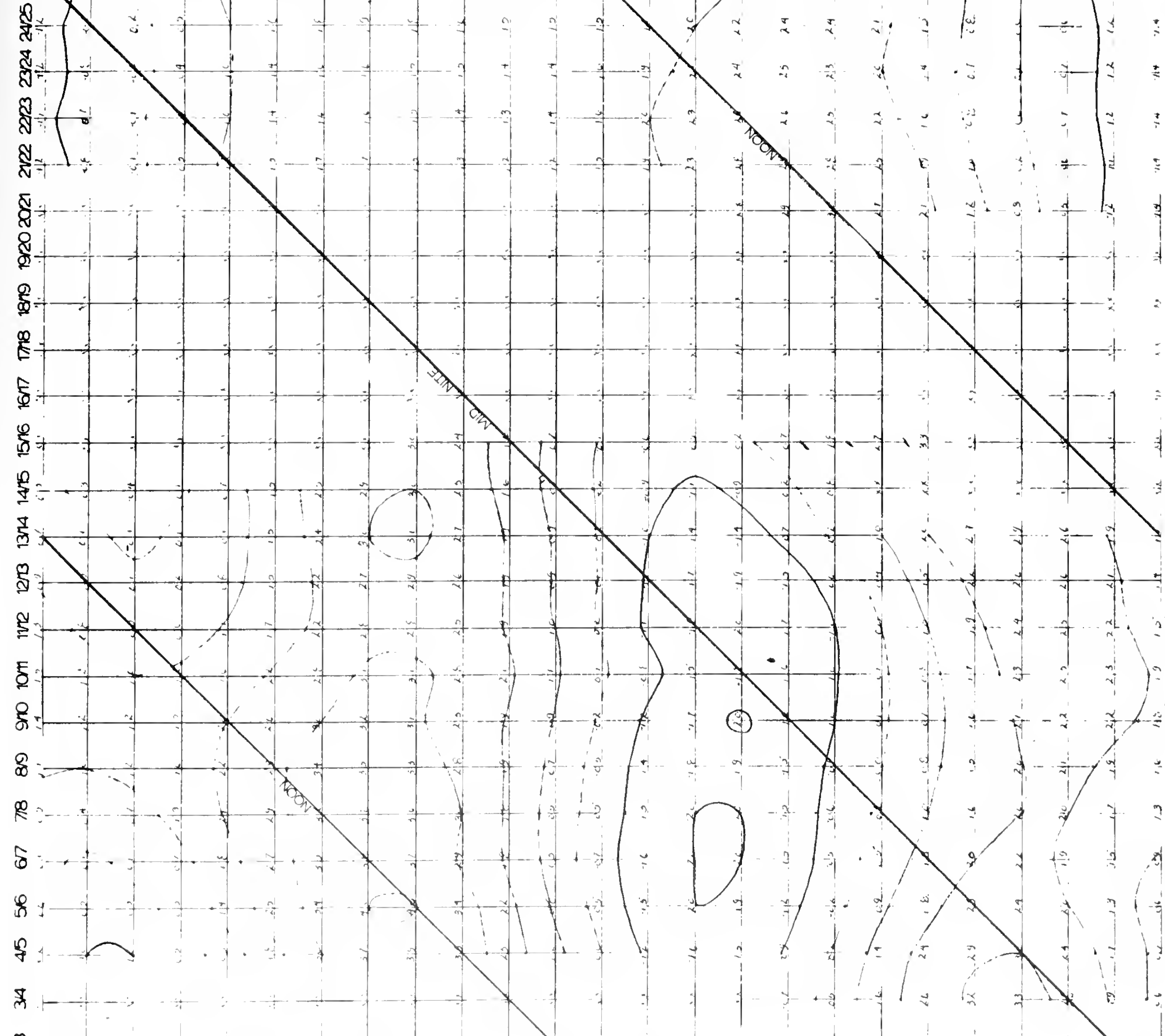


Figure 5. Observed Tides at Monterey in October, 1963.

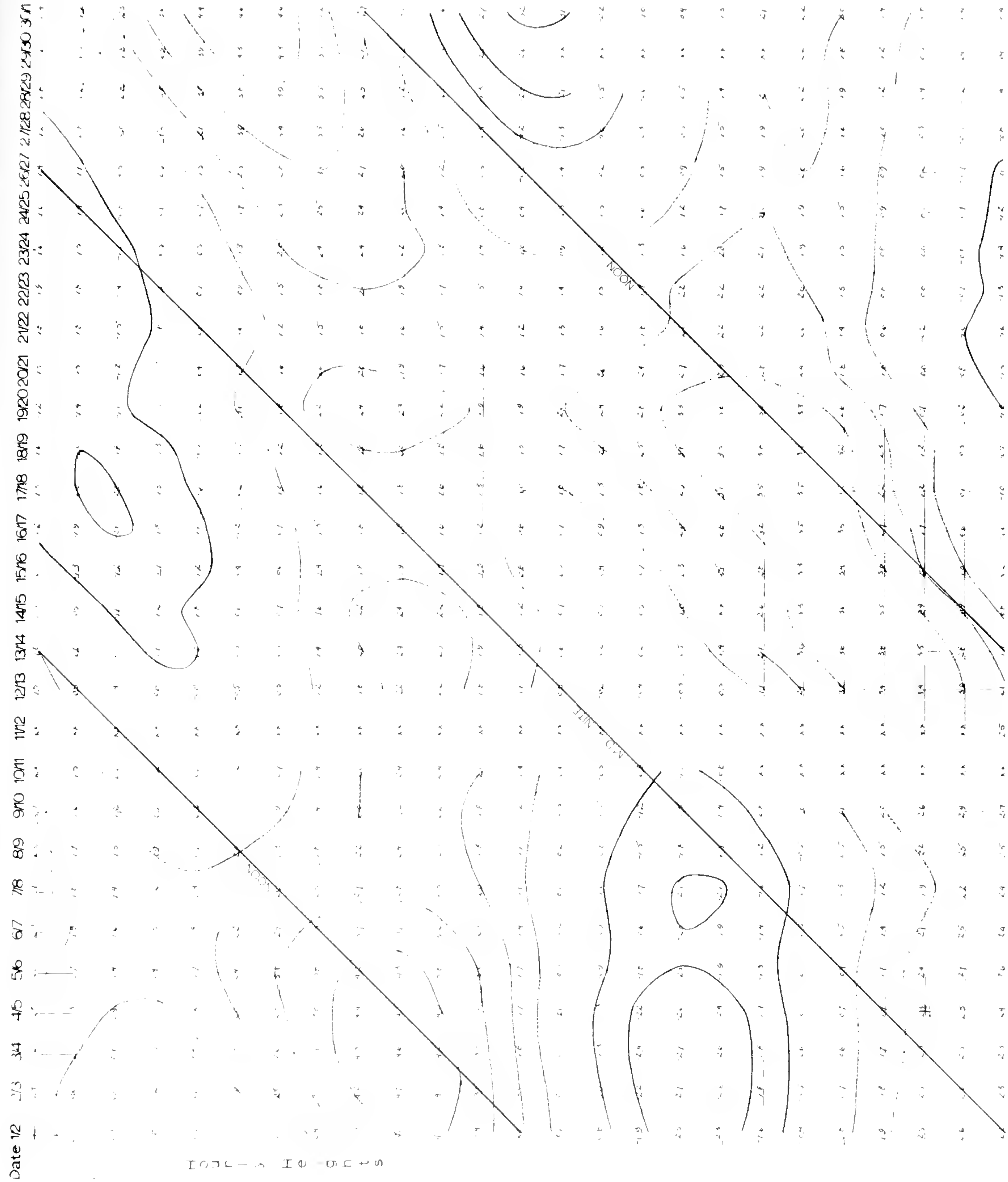


Figure 6 Observed Tides at Monterey in November, 1963.

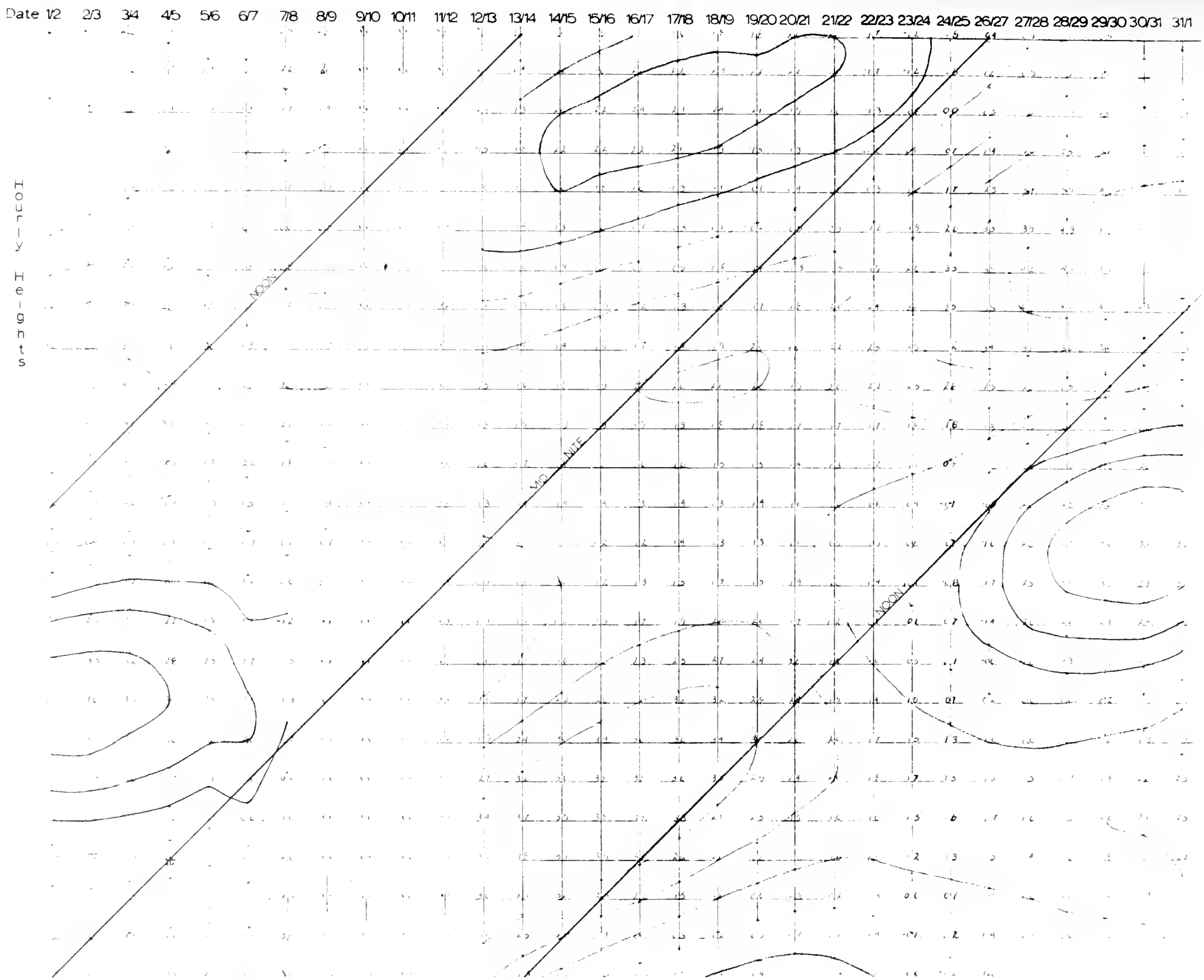


Figure 7. Observed Tides at Monterey in December, 1963.

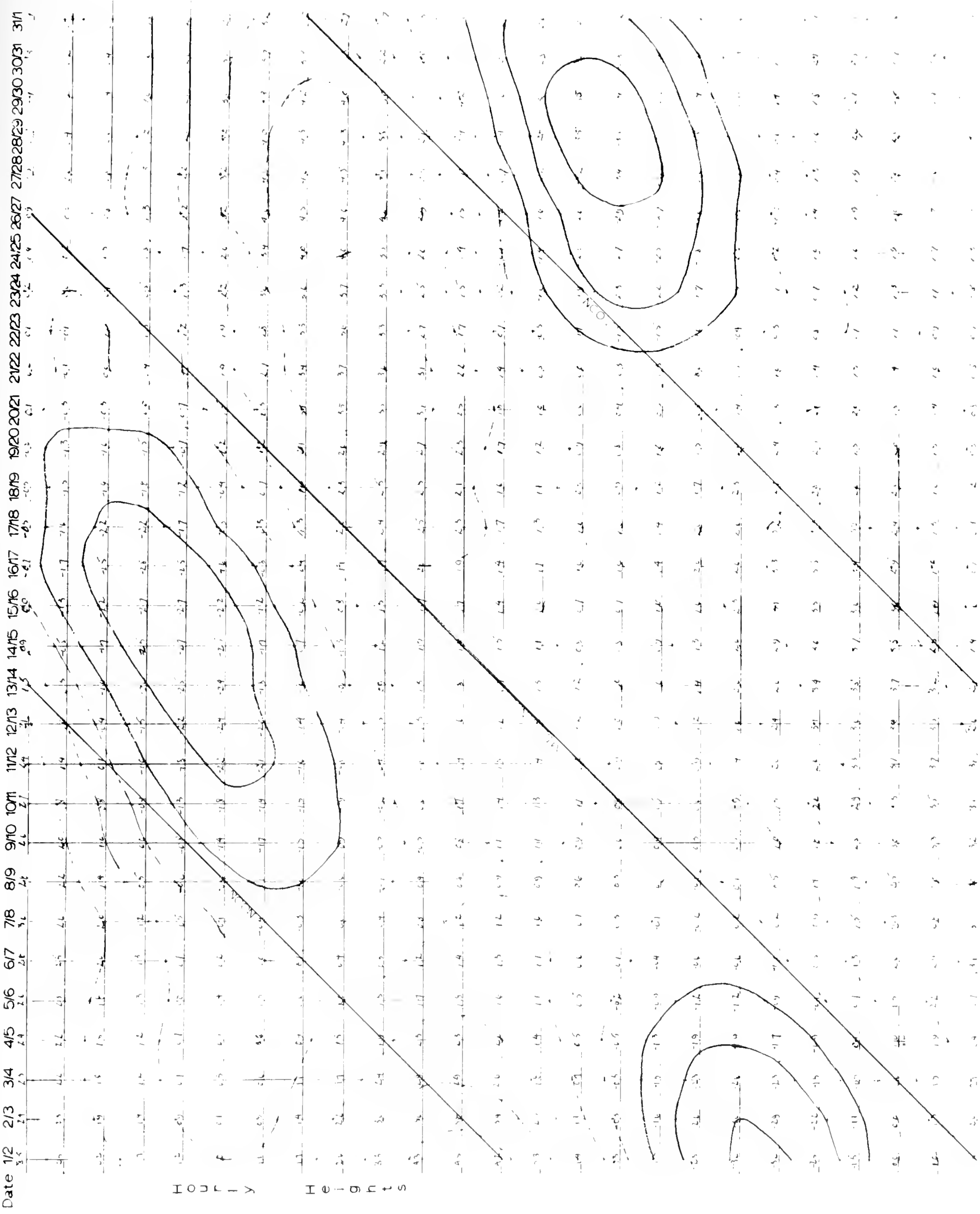


Figure 8. Observed Tides at Monterey in January, 1964

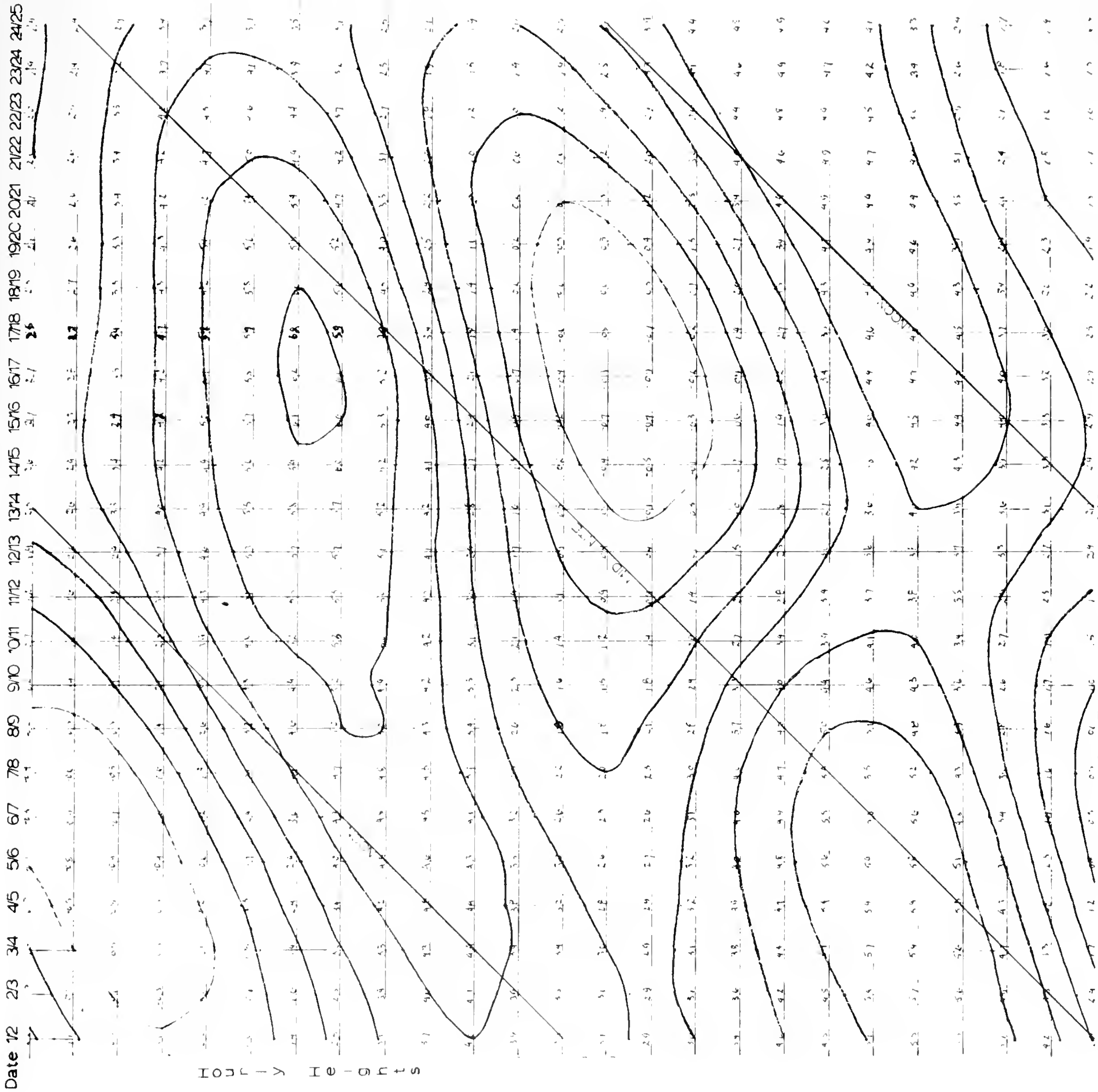


Figure 9 Astronomical Tides at San Francisco in August, 1963

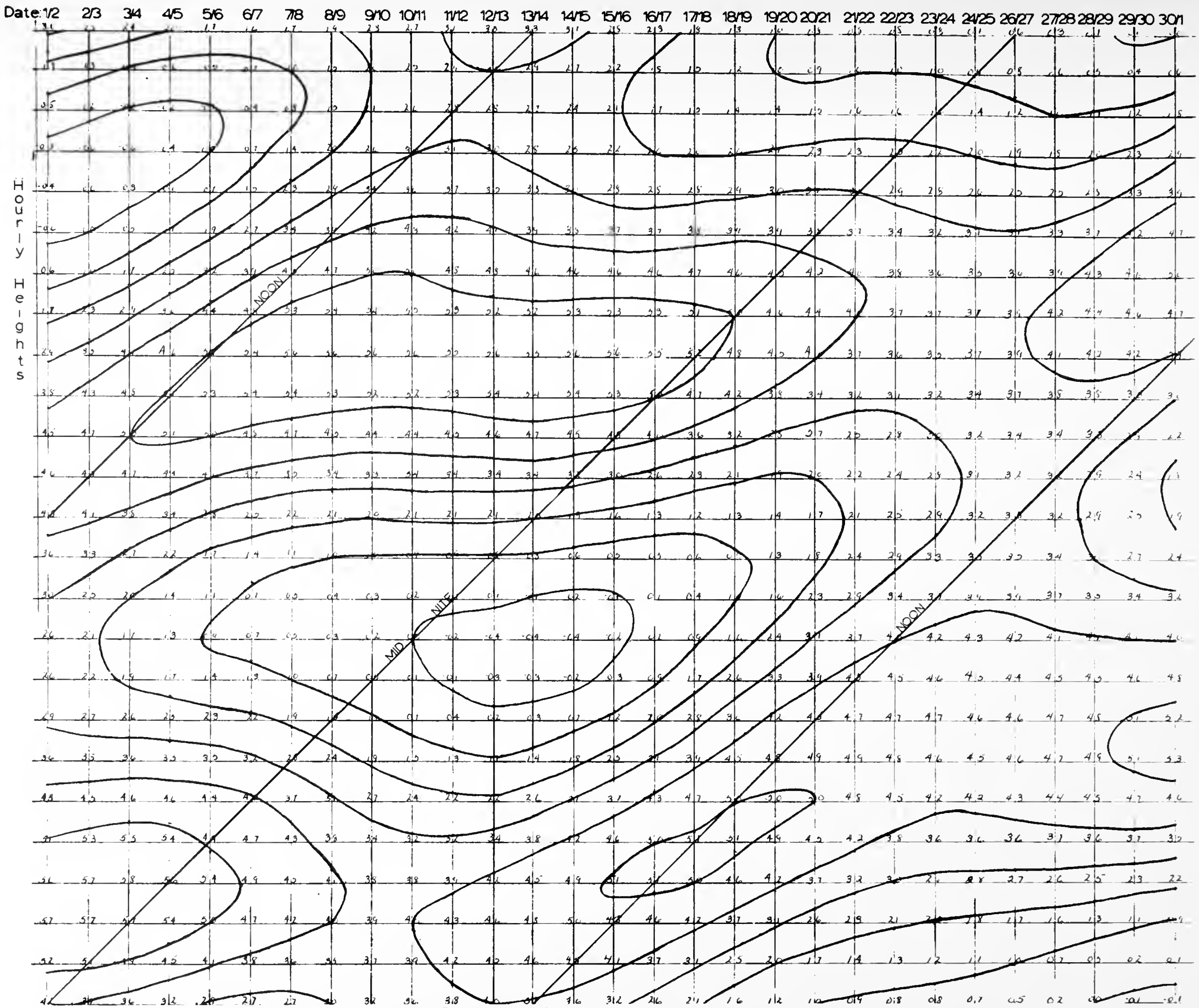


Figure 10. Astronomical Tides at San Francisco in September, 1963.

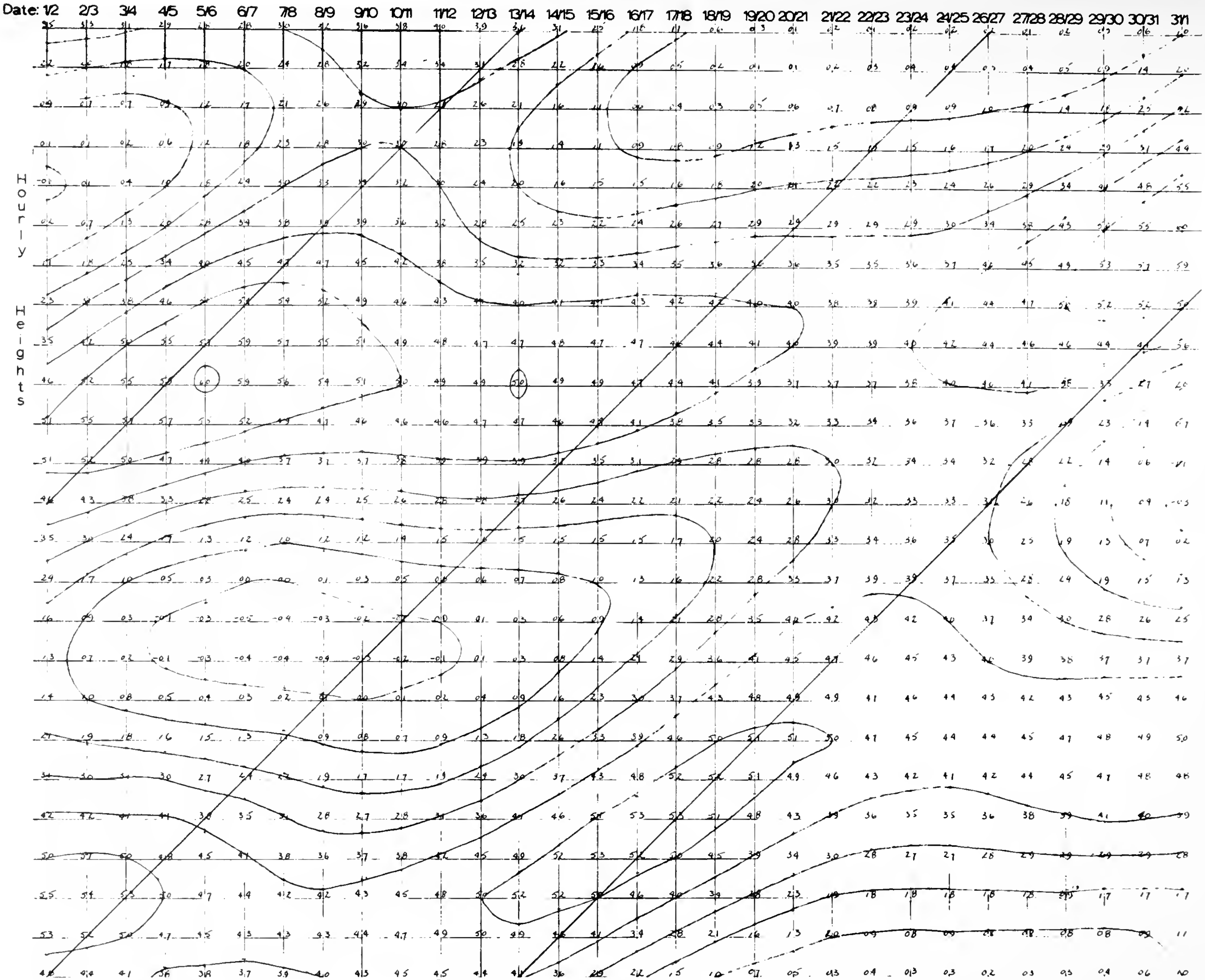


Figure 11. Astronomical Tides at San Francisco in October, 1963.

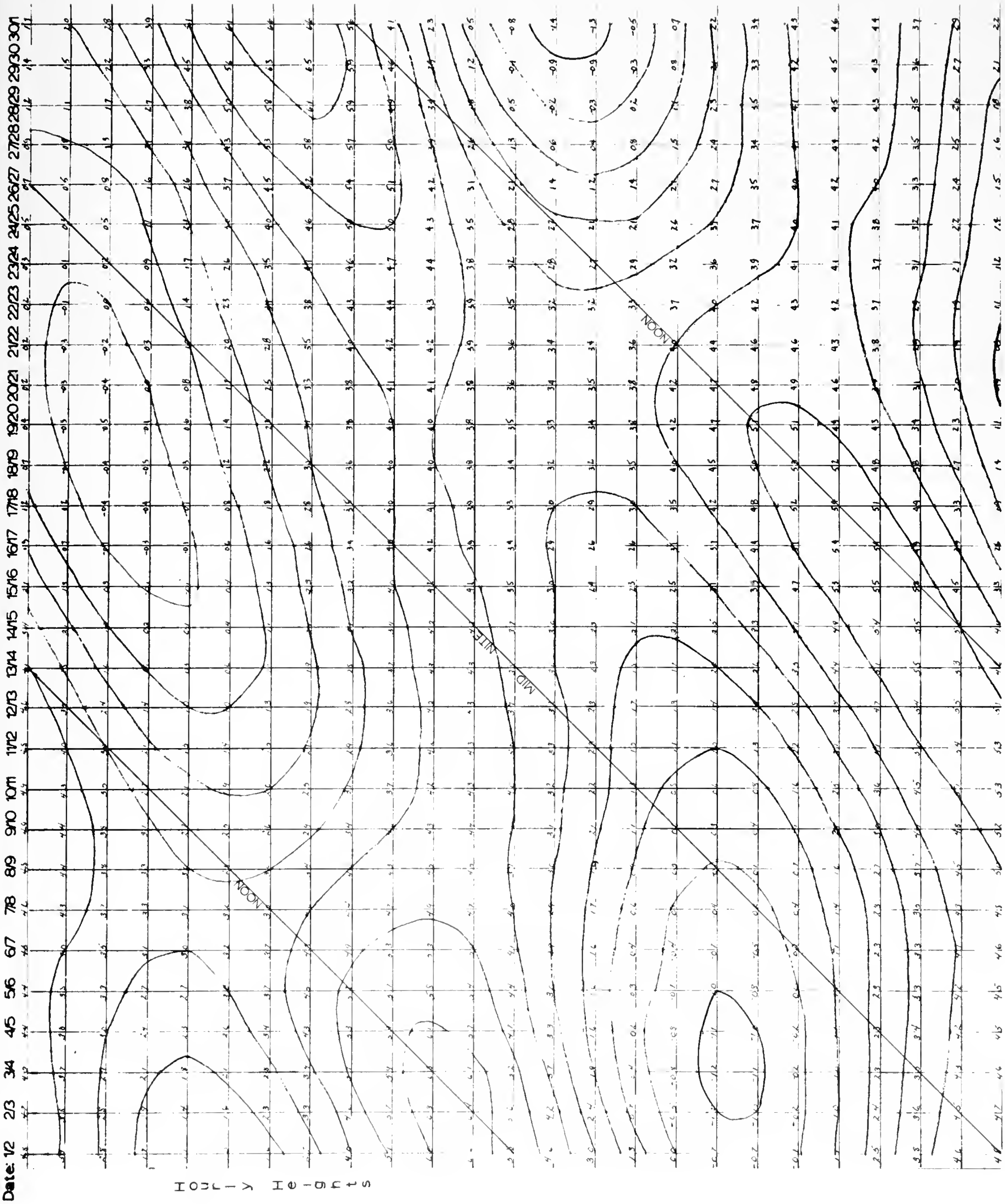


Figure 12. Astronomical Tides at San Francisco in November, 1963.

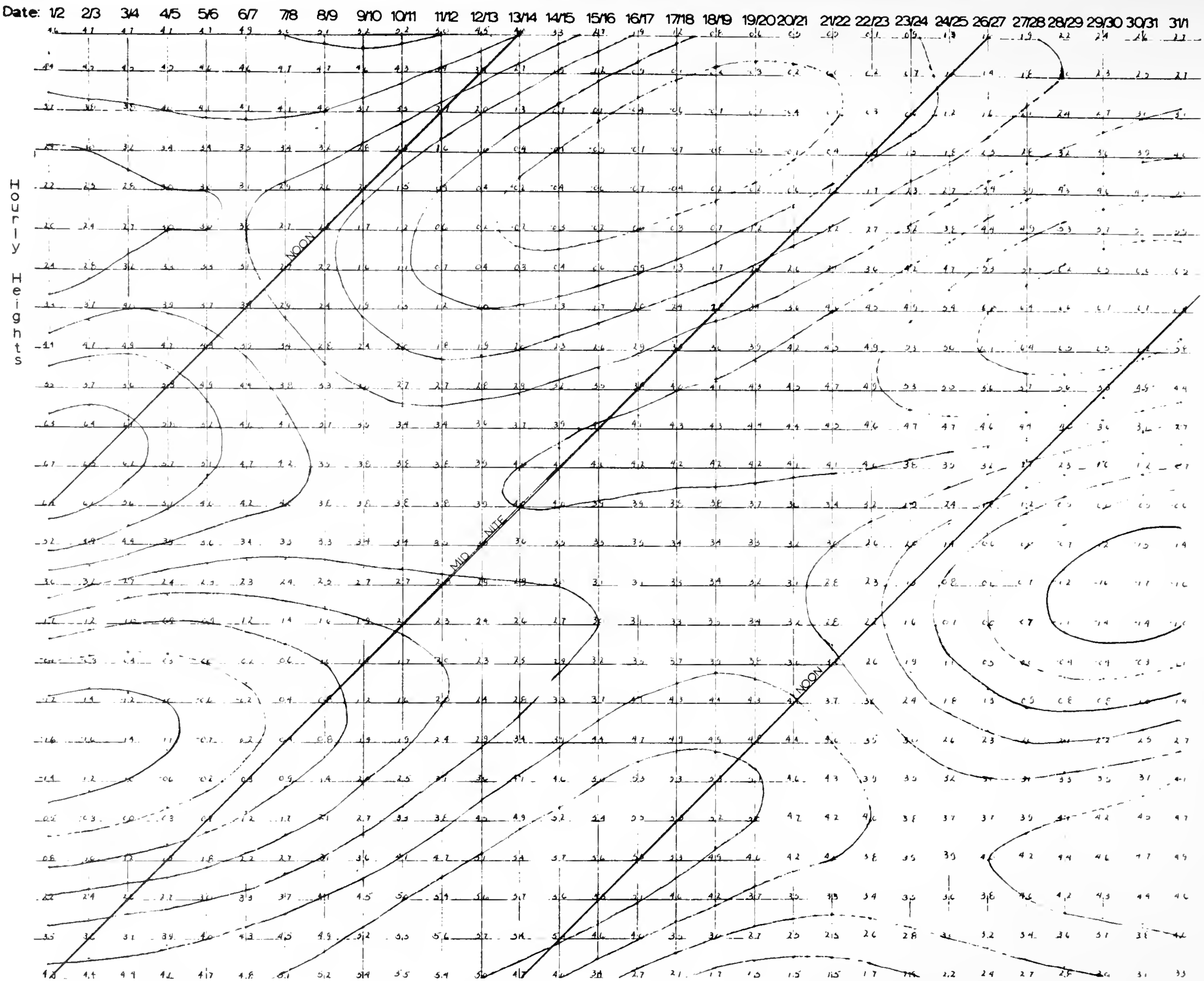


Figure 13. Astronomical Tides at San Francisco in December, 1963.

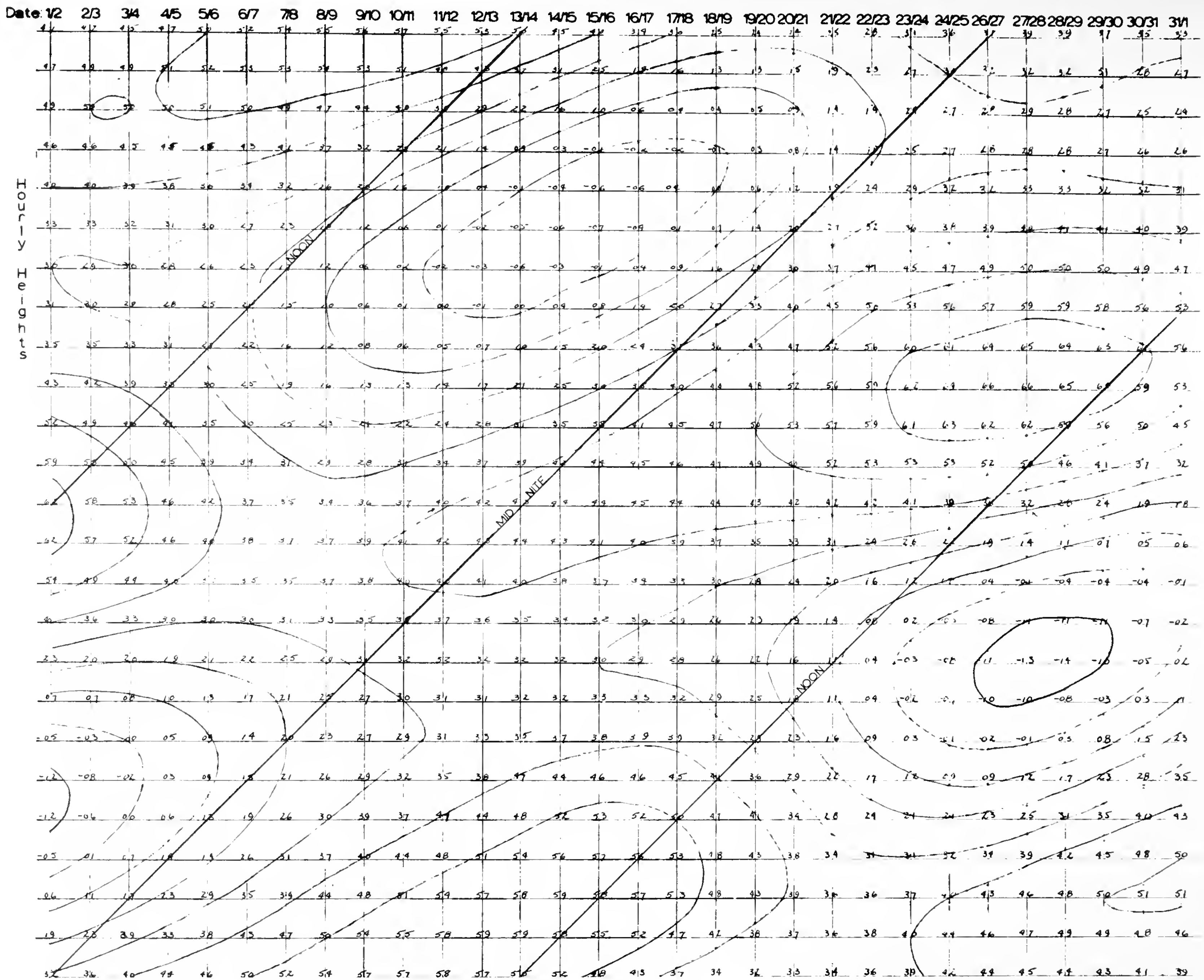


Figure14. Astronomical Tides at San Francisco in January, 1964.

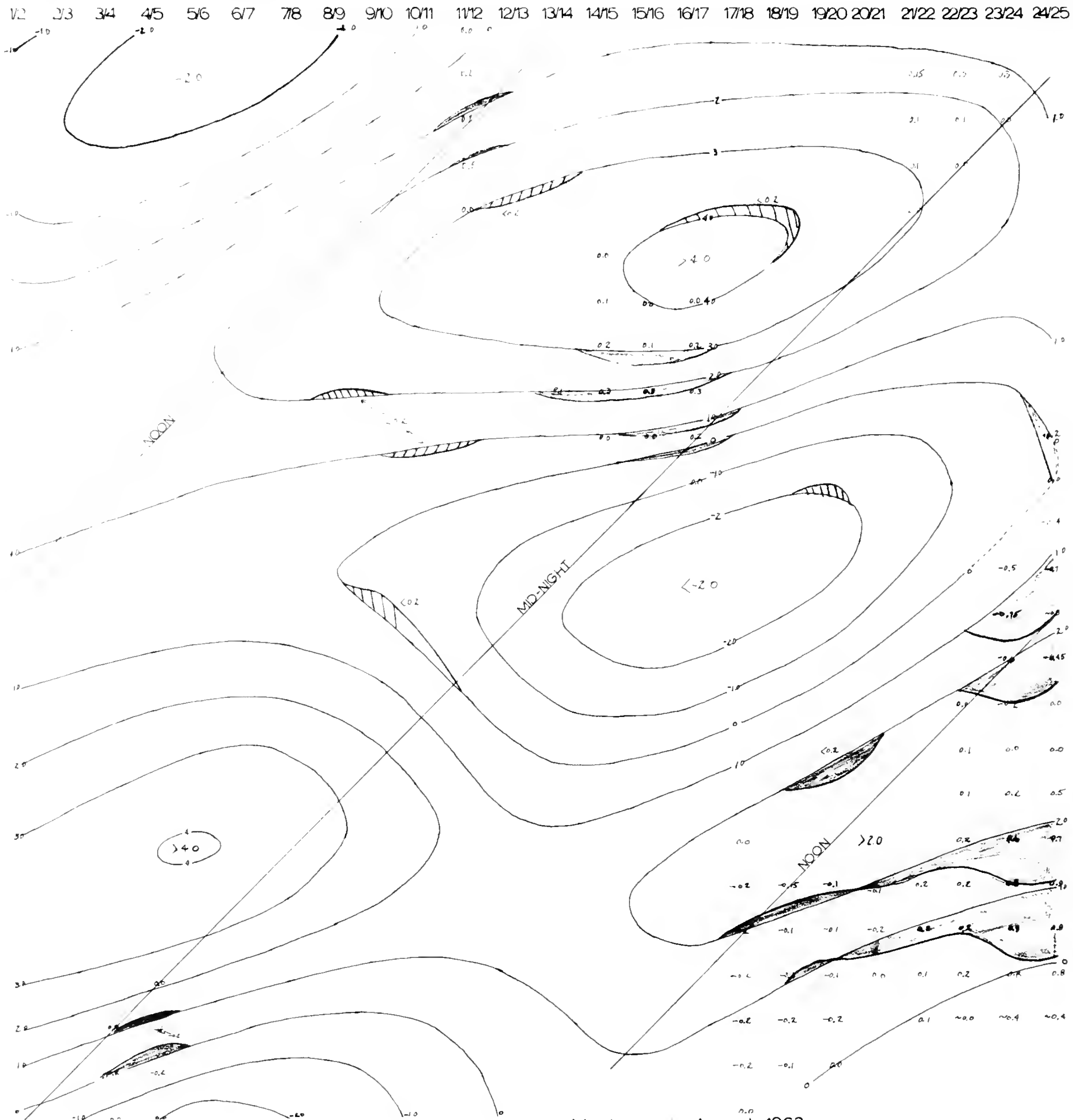


Figure 15. Astronomical Tides and Sea-Level Anomalies at Monterey in August, 1963.

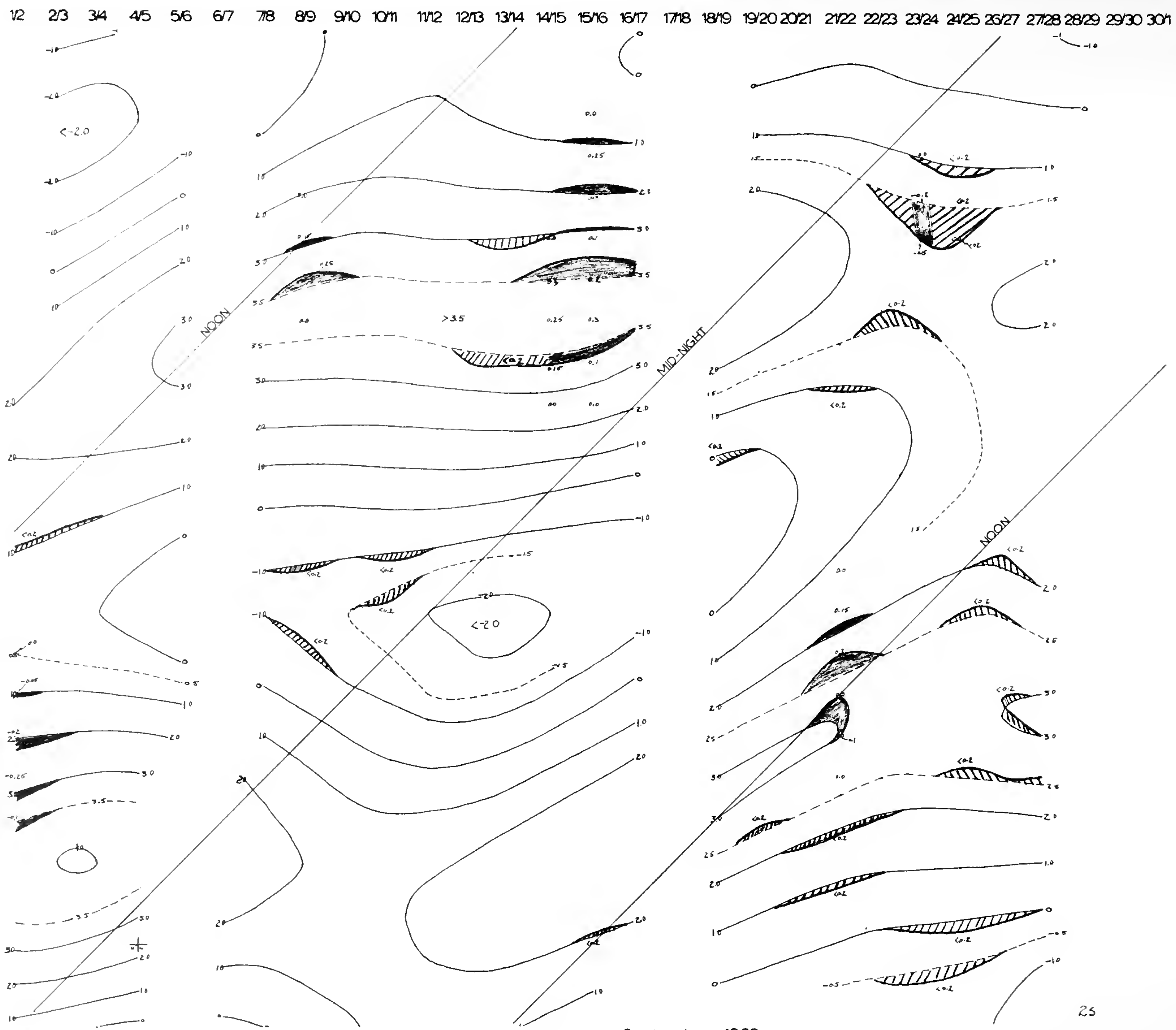


Figure 16. Astronomical Tides and Sea-Level Anomalies at Monterey in September, 1963.

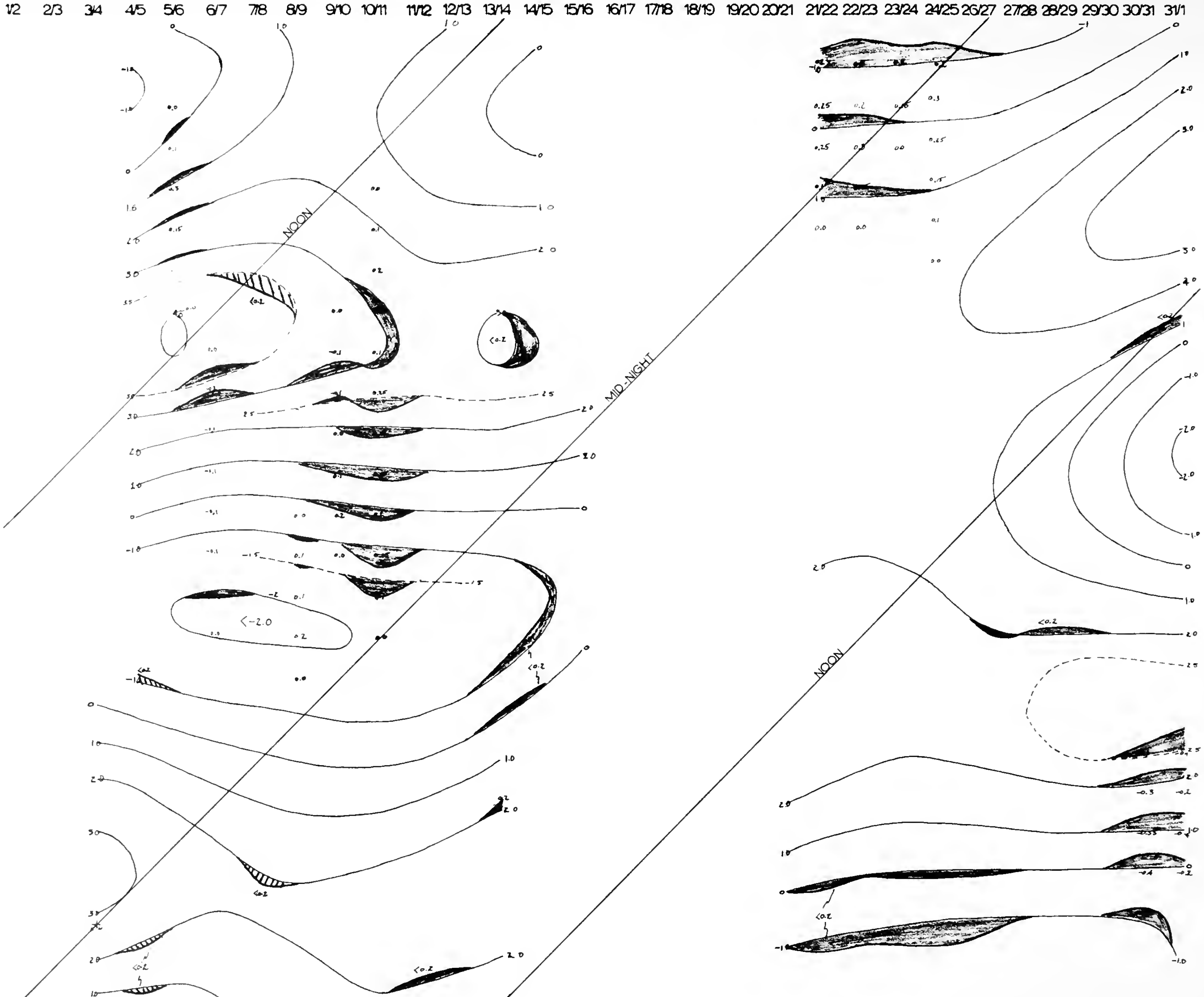


Figure 17. Astonomical Tides and Sea-Level Anomalies at Monterey in October, 1963.

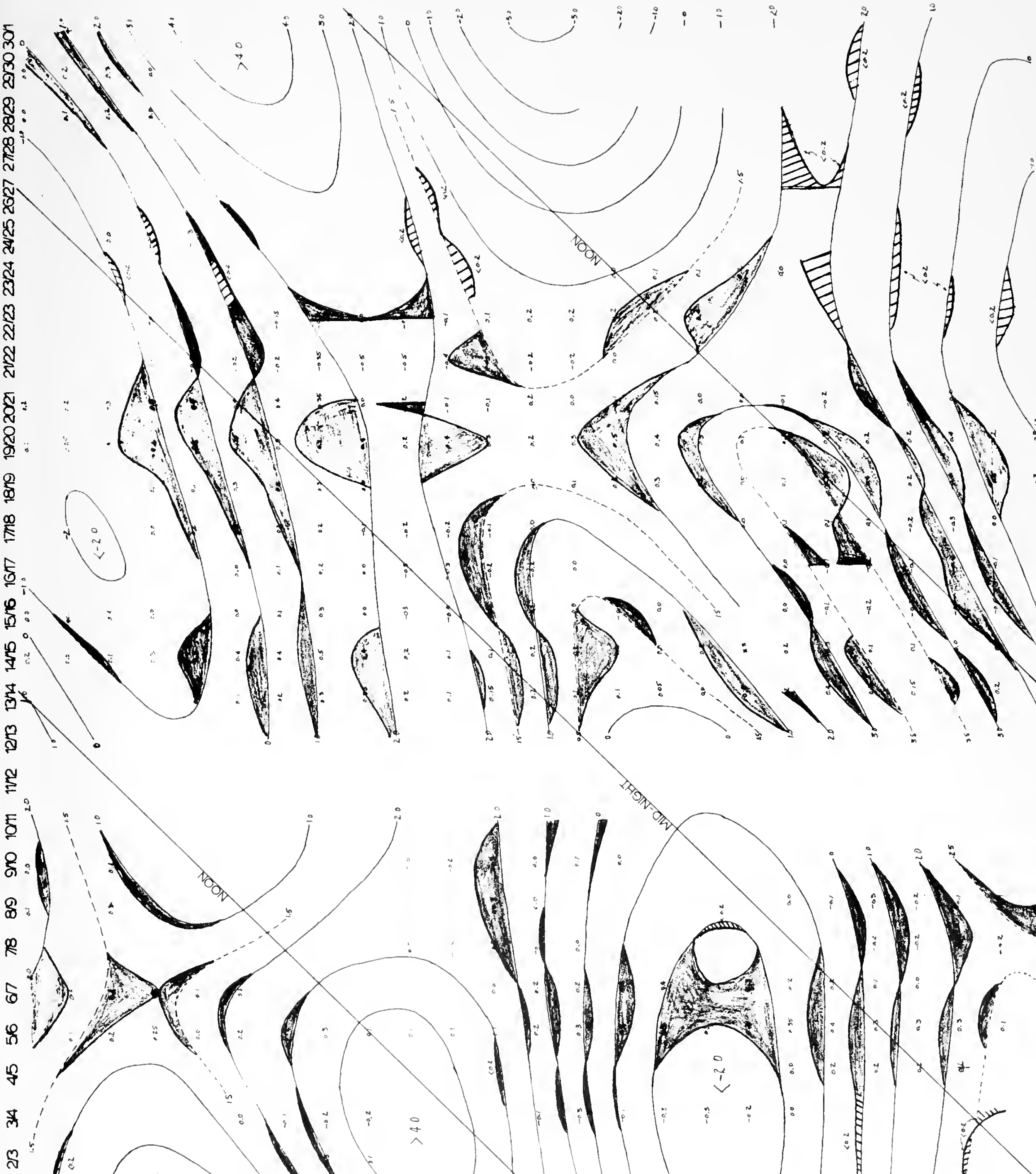


Figure 18 Astronomical Tides and Sea-Level Anomalies at Monterey in November, 1963.

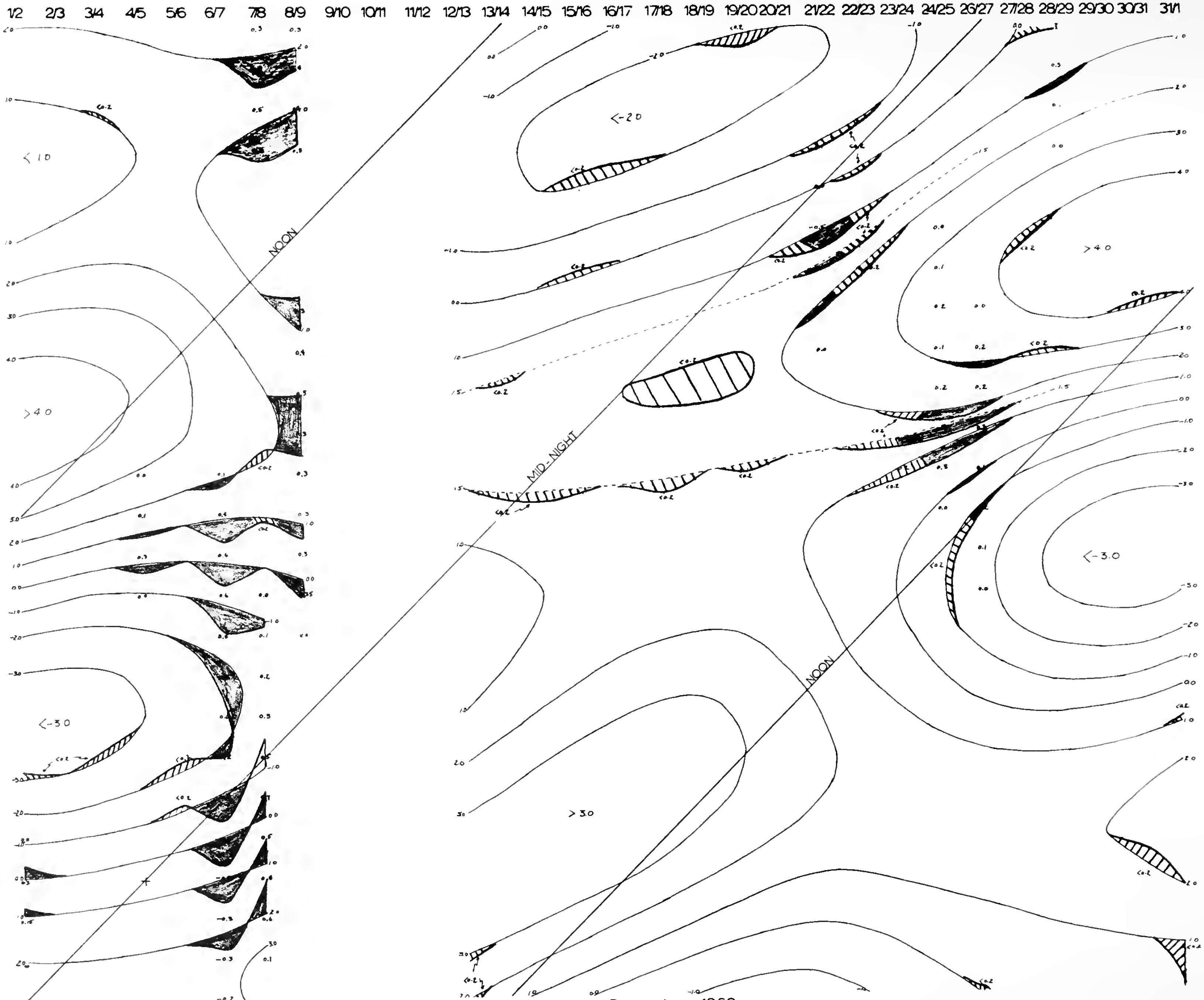
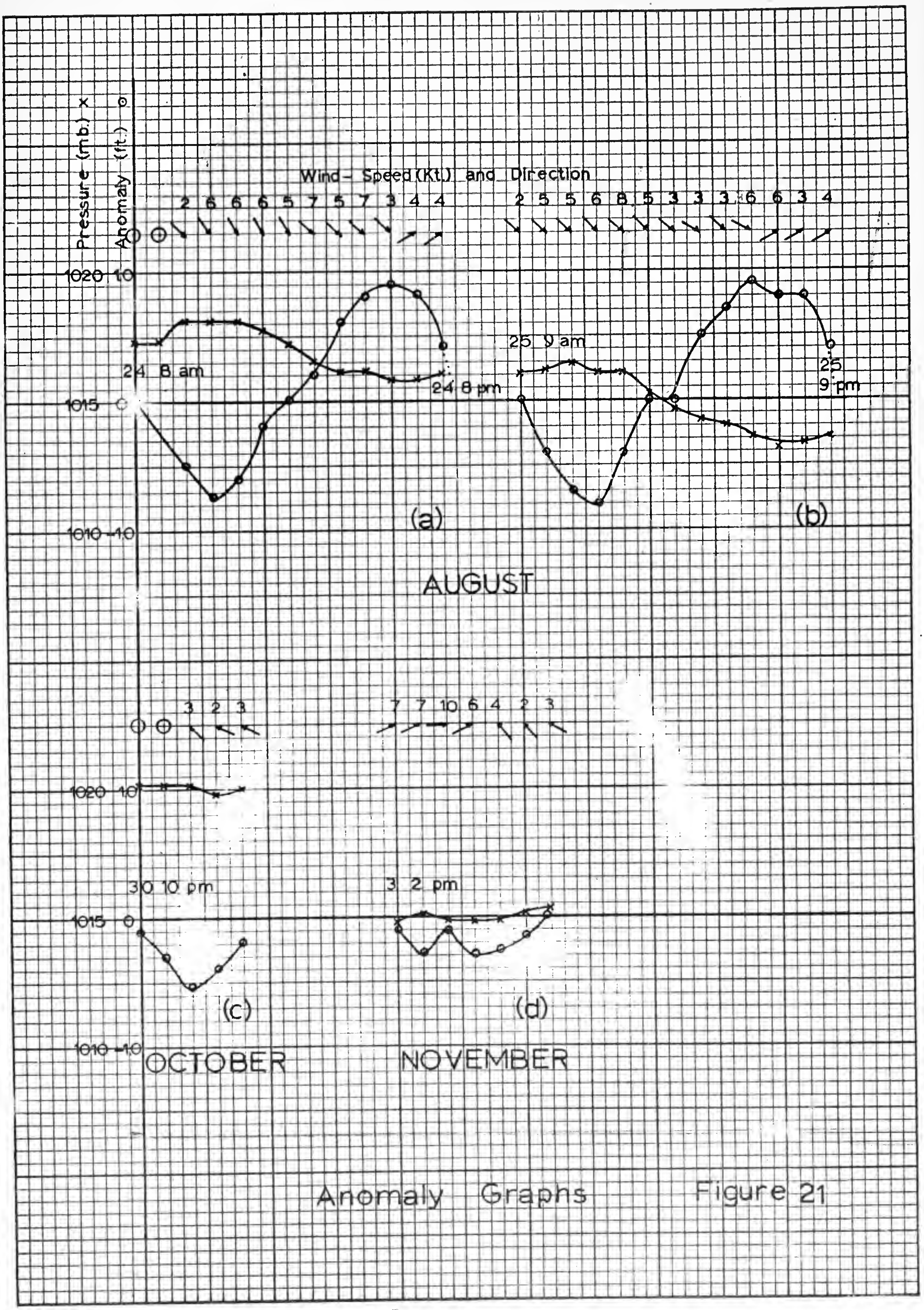


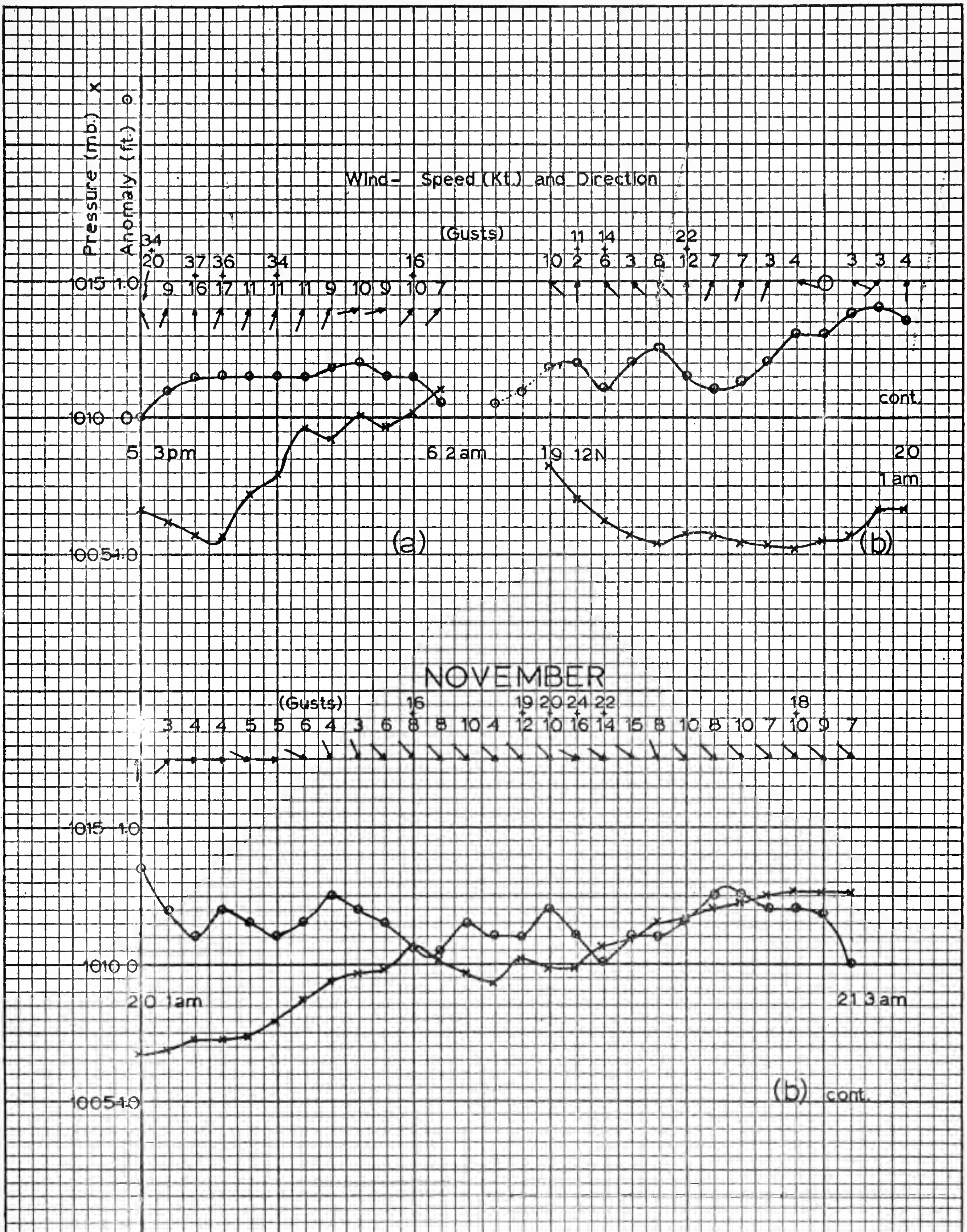
Figure 19. Astronomical Tides and Sea-Level Anomalies at Monterey in December, 1963.

Figure 20. Astronomical Tides and Sea-Level Anomalies at Monterey in January, 1964.



Anomaly Graphs Figure 21

7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



Anomaly Graphs Figure 22

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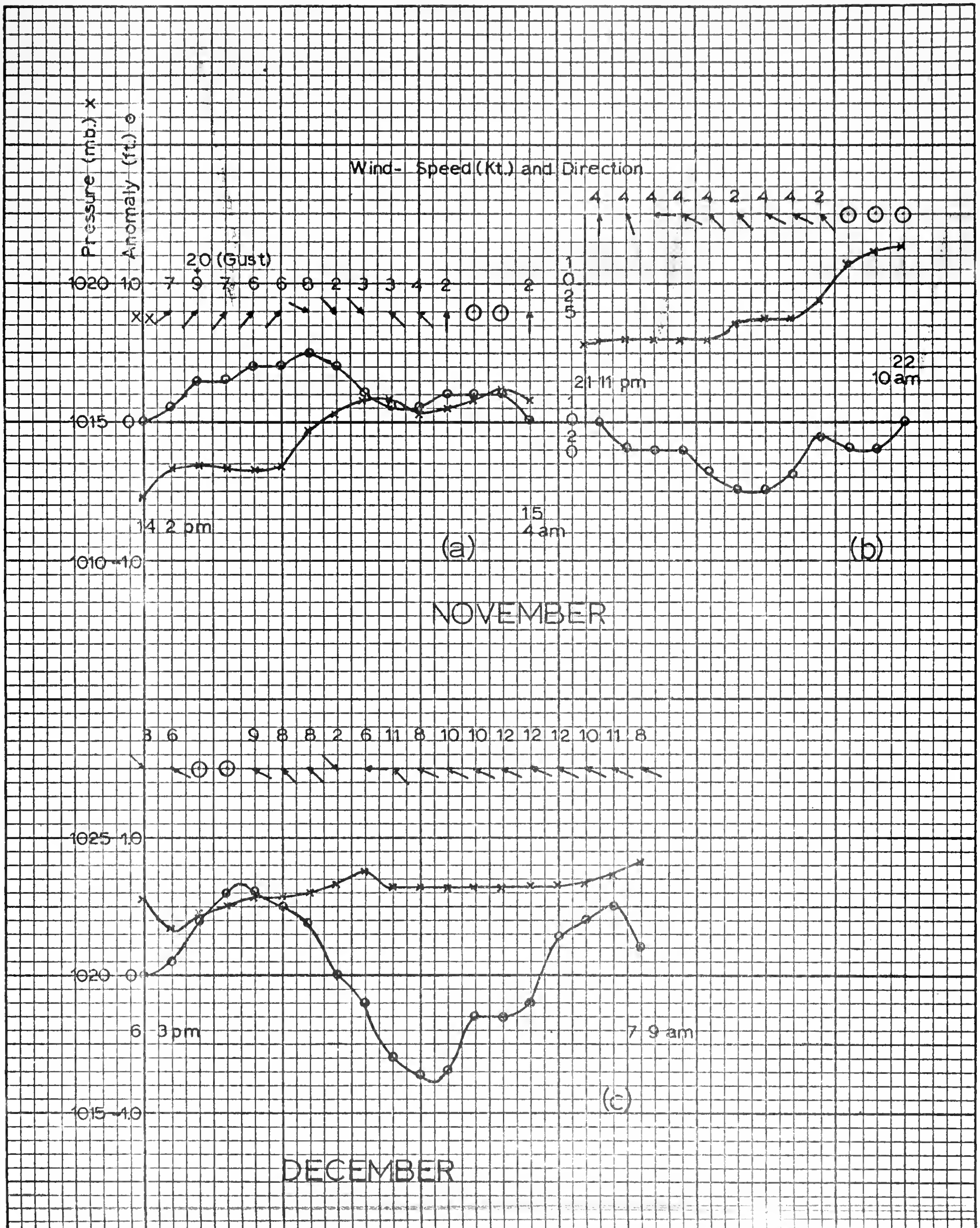

Anomaly Graphs Figure 23

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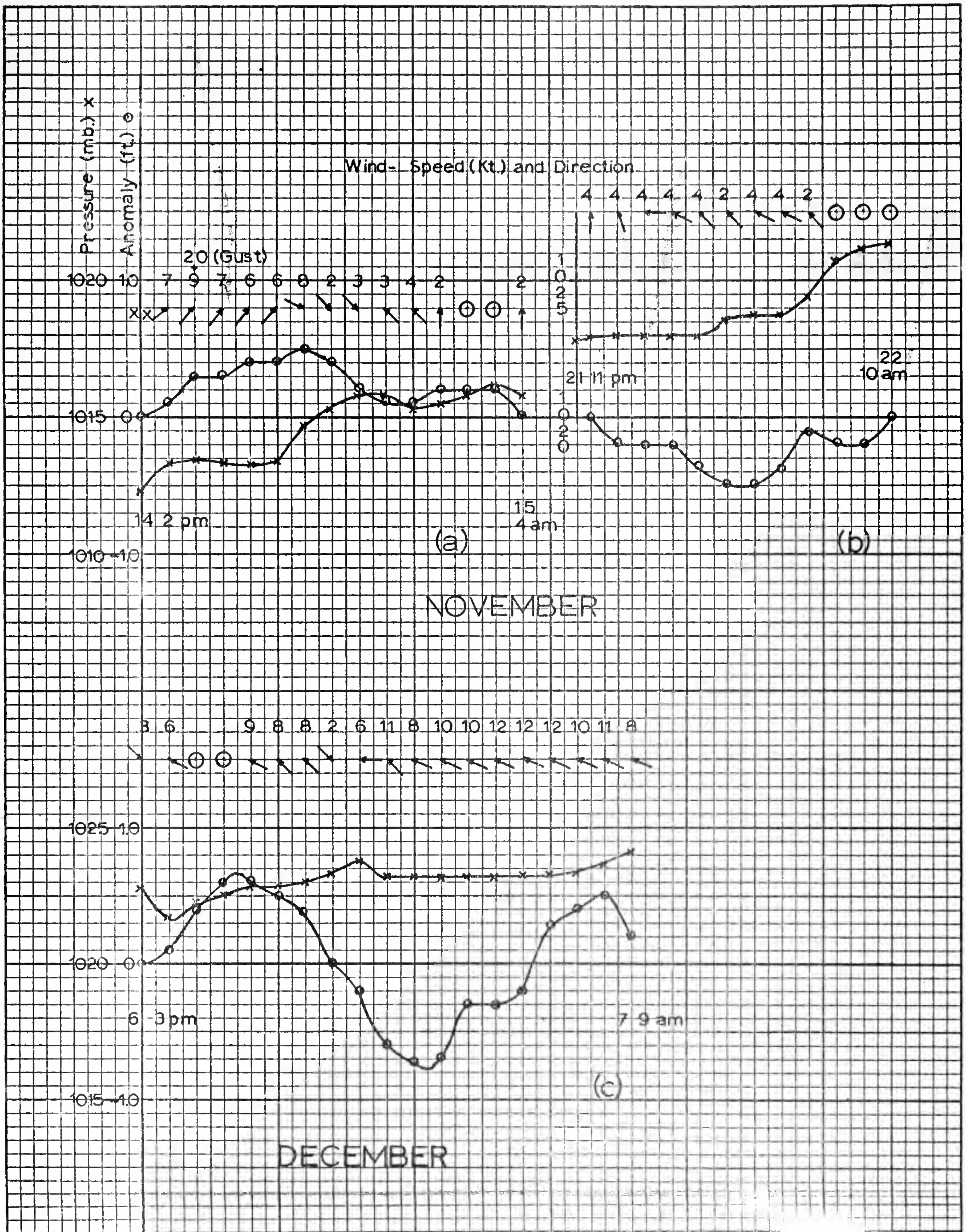
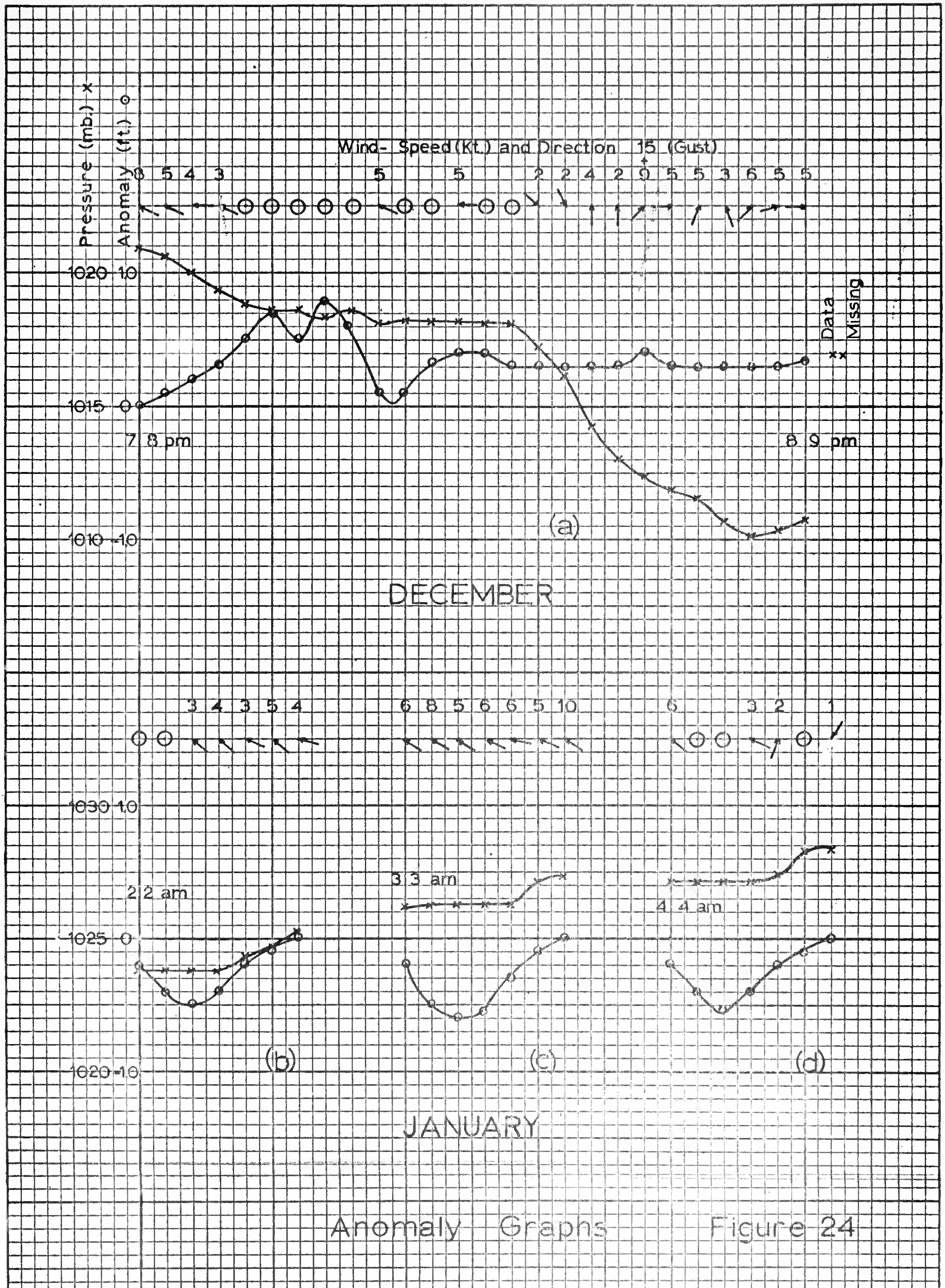


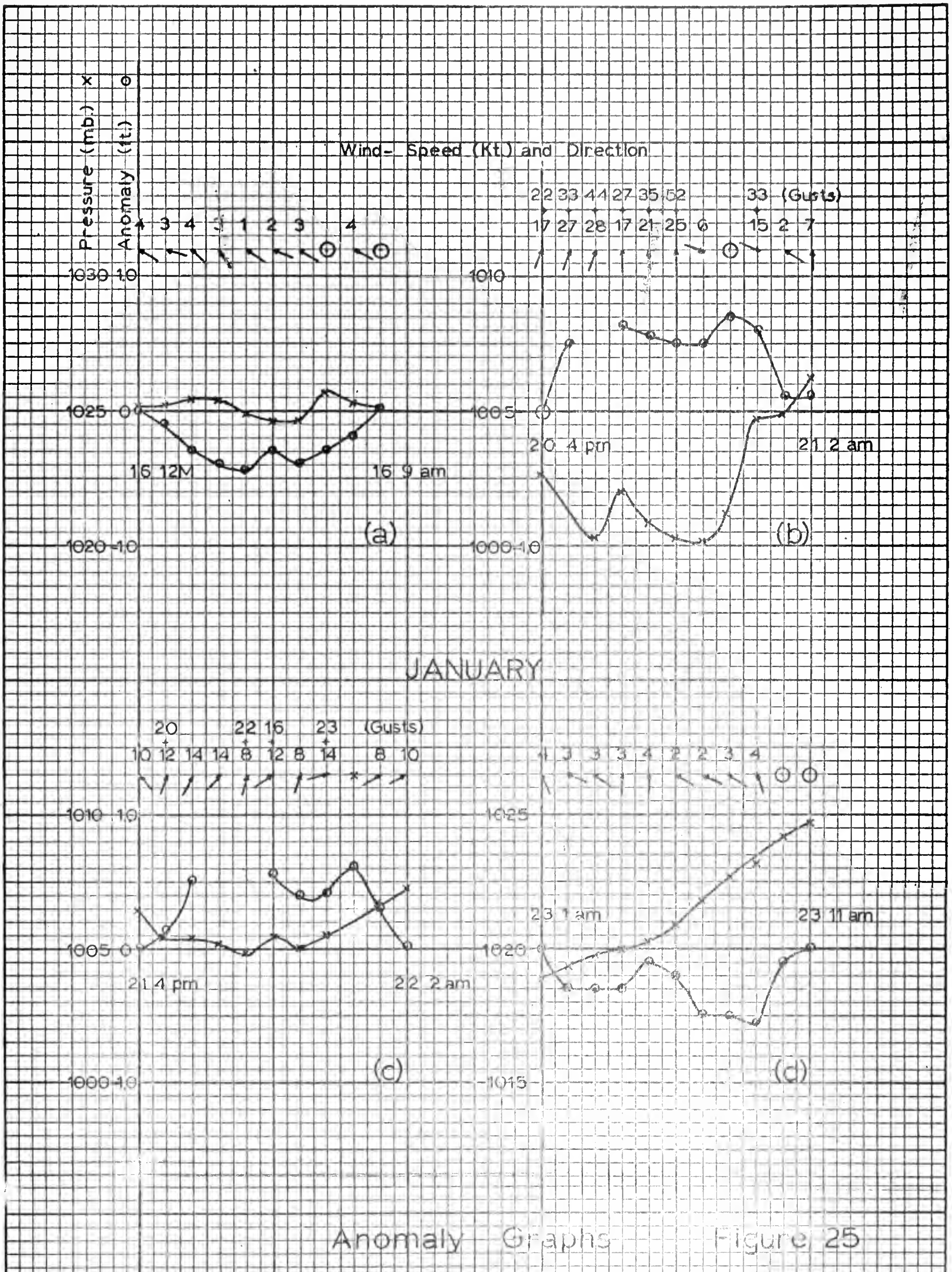
Anomaly Graphs Figure 23



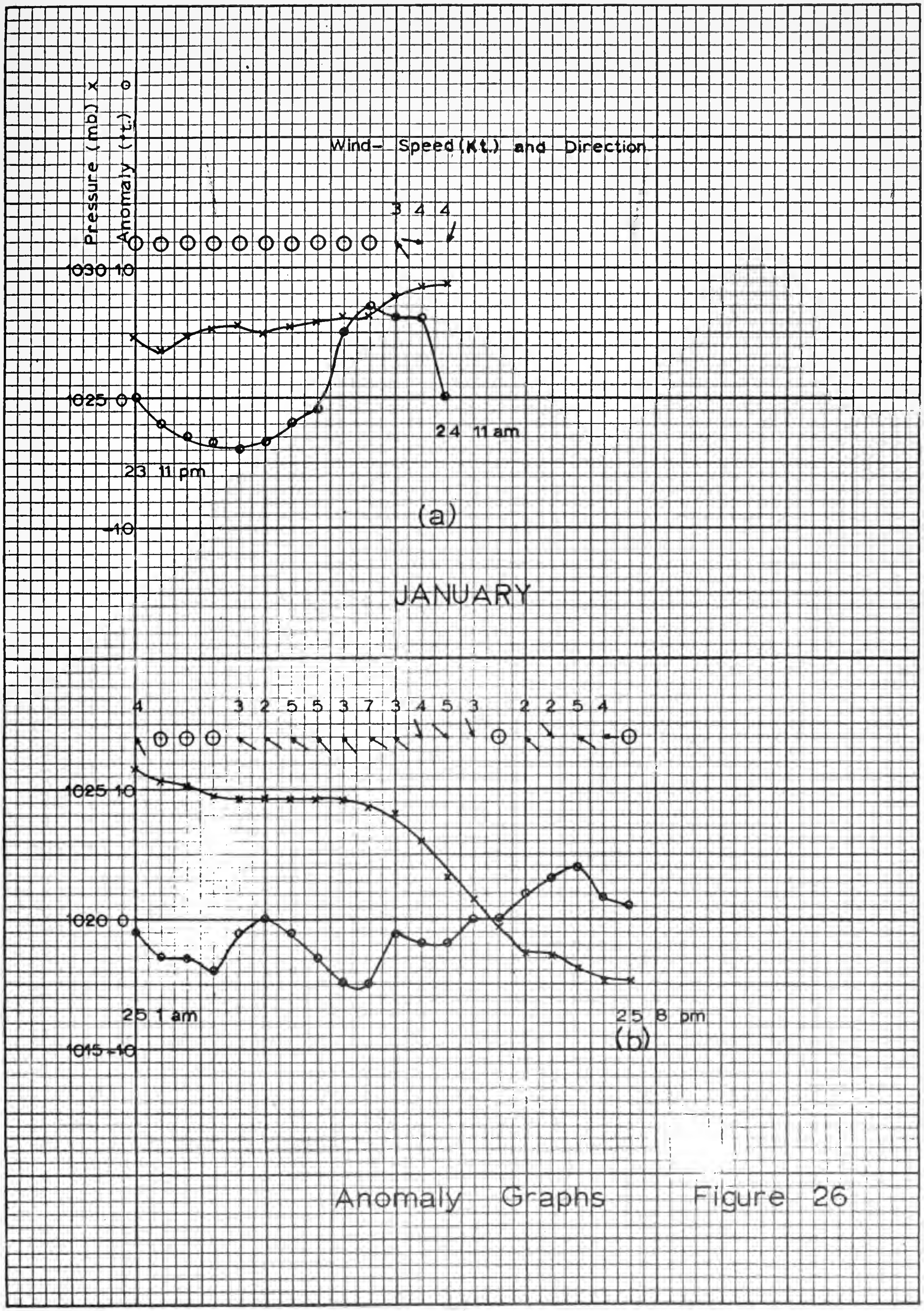
Anomaly Graphs Figure 24

K+E 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

KEUFFEL & ESSER CO. MADE IN U.S.A.



Anomaly Graphs Figure 25



Anomaly Graphs Figure 26

KEUFFEL & ESSER CO.